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NIAGARA 25 HZ SYSTEM ISLANDED OPERATION TESTS

Report No 90-309-K

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ABSTRACT

On April 16 and 17, 1989, a series of staged tests were performed to study the behaviour of the Niagara 25 Hz system while operating as an electrical island. Isolated operation settings were implemented on each of the Sir Adam Beck GS I 25 Hz governors to ensure a high level of damping when operating in the islanded configuration.

The tests confirmed that the existing system could be operated in the islanded configuration for extended periods of time without requiring any restrictions on the operation of customer equipment. Accurate models for the Voith electro-hydraulic governors have been developed based on manufacturer's data and detailed on-site testing for use in future operating and planning studies of the system.

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NIAGARA 25 HZ SYSTEM
ISLANDED OPERATION TESTS

1.0 BACKGROUND

The Niagara 25 Hz system is one of two remaining pockets of 25 Hz load/generation embedded in the Ontario 60 Hz system. The system is supplied primarily by generation located at the Sir Adam Beck I (SAB I) plant and the Ontario Power (OP) plant located on the Niagara river system. At the time that these tests were performed, five 25 Hz units were available at the SAB I plant (installed capacity approximately 200 MW) and twelve small units were available at the OP plant (installed capacity approximately 100 MW). During 1990 SAB I unit G8 was converted for 60 Hz operation, leaving only four units for 25 Hz operation.

The past configuration of the Niagara 25 Hz system (ie, prior to the tests) included three interconnections between the Niagara 25 Hz system and the 60 Hz system (refer to Figure 1):

- SAB I rotating frequency changer FC1, rated at 54 MVA
- 115 kV circuit A8W connecting SAB I GS (via Allanburg) to three frequency changers at Buchanan TS with a combined rating of 90 MVA.
- 69 kV circuit BSC105 connecting SAB I (via Niagara Parks TS) to several frequency changers on the 25 Hz Niagara Mohawk system in the United States, with an originally installed capacity of approximately 90 MVA.

The permanent connection between the 25 Hz system and the Buchanan frequency changers was removed on September 23, 1989.

The load connected to the 25 Hz system consists entirely of large industrial customers. Hamilton Gage TS, which is connected to SAB I GS via two 115 kV circuits, supplies two of the largest customers, Stelco and Dofasco. The load variations occurring at Gage TS were monitored in 1987 for the purpose of quantifying their behaviour, for inclusion in detailed models of the 25 Hz system [1].

1.1 Requirement for Test

On October 24, 1987, the SAB I frequency changer and the interconnection to Niagara Mohawk, BSC105, were removed from service to perform maintenance work at the SAB I plant. Upon opening of the Niagara Mohawk interconnection (BSC105), large power swings developed on the Buchanan frequency changers (which were in-service at this time) causing them to be tripped by their out-of-step protection and leaving the 25 Hz system in an electrical island.

A subsequent study of the system, performed by the System Planning Division (SPD), revealed that the incident occurred due to small signal instability. The instability results whenever the SAB I generators are connected to the 60 Hz system through a reduced number of frequency changers [2]. To control this problem, SPD recommended that fast-response exciters and power system stabilizers be installed on three of the 25 Hz units at SAB I. The first of these systems was installed and commissioned in April of 1990.

In early 1989 it was identified that the maintenance work at SAB I had become more urgent and that the outage to BSC105 and the SAB I frequency changer would have to take place prior to the installation of the power system stabilizers. It was decided by the Power System Operations Division (PSOD) and the Regions that an attempt should be made to perform the maintenance while operating the system as an electrical island (ie, all frequency changers disconnected from the 25 Hz system).

The System Planning Division performed numerous simulations to determine appropriate settings for the governors at Sir Adam Beck I GS to ensure frequency stability during islanded operation [3,4]. In addition, digital simulations were performed to establish the magnitude of frequency deviations which could be expected in the islanded configuration during normal operation of the rapidly-varying customer loads (ie, Stelco Rolling Mill). The Research Division was requested to supervise the implementation of the required governor settings and to participate in a controlled islanded-operation test of the 25 Hz system.

A detailed test plan was developed by all of the stakeholders [5] and the system was operated as an island between 11:27 (Daylight Savings Time) of Sunday April 16, 1989 and 10:17, Monday, April 17, 1989. Numerous quantities (ie, generator output power, gate position, terminal voltage) were monitored during the extended islanded operation to provide detailed data for use in future planning and operating studies of the system.

1.2 Organization of Report

Section 2 of this report documents the results of the staged islanded operation tests including a number of observations pertaining to future operation of the system in an islanded configuration. Section 3 of the report contains data and modelling information obtained during detailed testing of the governors on the five 25 Hz generators at SAB I GS. Section 3 will be of interest to readers requiring detailed information on the configuration and modelling of the Voith electro-hydraulic governor.

2.0 ISLANDED OPERATION TESTS

Prior to operating the system in an islanded configuration, tests were performed on the governors of each of the five SAB I GS units. The main goal of these tests was to implement and confirm System Planning Division's recommended isolated operation settings on each of the units. Due to differences between the governors on the five units, it was not possible to implement the settings exactly as specified. Table 1 provides a list of the governor settings used for the bulk of the islanded testing (refer to Section 3 for complete details).

The primary objectives of the islanded operation tests were to:

- ensure that the isolated operation governor settings provided the necessary damping of the speed/load control loop.

- ensure that system frequency and voltage variations remained within reasonable bounds during all normal customer load variations.

A brief summary of the test procedure, used to verify that these objectives were met, is listed below along with the numbers of the sub-sections which contain the corresponding test results:

- (2.2) Create the island by systematically opening the interconnections to the 60 Hz system.

- (2.3) Reject one of the SAB I generators from partial load and monitor the response of the remaining machines and system.

- (2.4) Monitor start-up of Stelco's large synchronous motor sets (7500 HP, 9800 HP).

- (2.5) Monitor system during normal customer load variations.

- (2.2) Exit the island by reconnecting the 25 Hz system to the 60 Hz system via one or more frequency changers.

2.1 Instrumentation/Monitored Quantities

Given the importance of the SAB I GS governor settings to the overall response of the system, a substantial portion of the installed instrumentation was aimed at monitoring each governor's response to the various staged tests. In addition to the individual unit quantities, the system frequency and 115 kV bus voltage were also monitored at SAB I GS during the tests.

Previous testing [1] had demonstrated that the normal operation of the Stelco East (Strip) Mill and Cold Roll Mill loads produced large repetitive step changes in the real power demand. In addition, the operations groups expressed some concern regarding the anticipated response of the islanded system to the starting of Stelco's large synchronous motors (3 x 7500 HP, 2 x 9800 HP). Based on the above, additional instrumentation was situated at Hamilton Gage TS to directly monitor Stelco load variations. A telephone communication link between S.A. Beck GS and Gage TS was used to synchronize measurements performed at the two locations.

A complete list of the measured quantities at the two locations is provided in Table II for reference purposes. Selected transducer outputs were monitored on chart recorders and a digital data acquisition system during each of the tests.

2.2 Entering and Exiting the Islanded System

The following generating conditions were established prior to opening the interconnections with the Ontario Hydro 25 Hz system:

- All five S.A. Beck I GS 25 Hz units were synchronized to the system. Beck I G7 was parallelled to the Ontario Hydro system prior to the test (normally connected radially to the Niagara Mohawk system).

- All available Ontario Power GS units (eleven) were placed in-service at speed-no-load.

- The direct connection between the Canadian Niagara Power (CNP) GS generators and the Ontario Hydro system was removed.

The five Beck I generators were configured for islanded operation; on the Voith electro-hydraulic governors (G1, G2, G7) this involved manually selecting the isolated mode of operation while on the I.P. Morris mechanical-hydraulic governors (G6, G8) dashpot needle valves were closed in order to obtain the desired reset times (refer to Table I).

Customer load variations were at a minimum prior to the test due to the start time (Sunday morning, 11:27 Daylight Savings Time, April 10, 1989) which was selected to coincide with a partial shutdown of Stelco's load.

The flow on 115 kV circuit A8W was balanced to zero and the circuit removed without any significant voltage or power changes. Beck I generation was adjusted to unload Beck FC1 and the frequency changer was disconnected without incident. The remaining interconnection to the

60 Hz system consisted of the Niagara Mohawk Gardenville frequency changers connected via circuit BSC105 (Lockport frequency changer was out-of-service prior to the test). Opening circuit BSC105 produced small changes in the system frequency and 115 kV voltage, measured at Beck I, but virtually no change in the outputs of any of the Beck I generators. Figure 2 displays some of the measured quantities; the real power outputs for G1 and G2 have also been displayed as examples of the unit responses. After completion of the islanded test the reverse procedure was used to exit the island; ie, circuit BSC105 was reconnected at S.A. Beck I GS followed by the reconnection of Beck FC1 and circuit A8W to Buchanan TS. Although the closure of BSC105 did not result in a significant disturbance on the Niagara 25 Hz system, information received after the test indicated that the flows on the Gardenville frequency changers temporarily exceeded their normal operating limits due to the rapid variations in Stelco load. Future operating procedures may be modified such that restoration is delayed until customer load variations are at a minimum.

2.2.1 Ambient Monitoring

Given the light load conditions, only 32 MW of generation at S.A. Beck I GS was required to maintain the frequency at 25 Hz; CNP generation was disconnected from the island and the OP generators (eleven total) were operating at speed-no-load. Each of the Beck I units was operated at partial gate and the load was evenly distributed between the five generators. Under these ambient light-load conditions, there was little or no change in system frequency or voltage. The maximum peak-to-peak deviations in these two quantities measured over a period of several minutes were within 0.5% (frequency) and 1.0% (115 kV voltage).

During the ambient monitoring period an unexpected increase in frequency occurred (+1.5%) causing the governors to rapidly close their gates returning the frequency to within 0.2% of 25 Hz. It was later identified that this brief transient was due to the Cyanamid load increasing to approximately 15 MW and then disconnecting suddenly without explanation. Although all recorders were set at very low speeds, it was clear that the system and individual unit responses to this sudden load change were very well damped.

2.3 Generation Rejection Tests - S.A. Beck I GS

Prior to permitting Stelco to synchronize its large motors to the system, a number of staged tests were performed at the Beck I plant to study the response of the governors to sudden load/generation mismatches.

As a preliminary step, the power on unit G8 was varied by gradually adjusting the gate position between 17% (6 MW) and 37% (18 MW), then returning it to its original position. Despite the fact that the remaining four units had identical permanent speed droops, (0.04 pu speed/pu gate), the bulk of the generation changes were distributed amongst the three units (G1, G2, G7) outfitted with the electro-hydraulic governors. This was not necessarily surprising since the mechanical flyball governor on G6 was expected to have a relatively larger speed dead band and the total frequency deviation during the load ramping was under 0.5%.

Following this test, G8 was loaded to 10 MW and rejected via its unit breaker producing the frequency and voltage swings plotted in Figure 3. The peak frequency deviation following the unit rejection was -1.2%. Referring to Figures 3a) and 3c) it can be seen that the frequency/gate transient was extremely well damped due to the selection of the isolated operation settings on the governors. It is noteworthy that G6 exhibited the largest gate position movement of the four remaining units. The reason for this was the relatively lower settings for both the temporary droop and the damping time constant (refer to Table I) on G6. The three units equipped with Voith governors had almost identical gate responses to the 10 MW generation loss.

The generation rejection test was repeated several times including once with the Ontario Power GS units taken out-of-service. The results obtained were virtually identical for each of the tests; with the Ontario Power GS units out-of-service the peak frequency deviation following the 10 MW generation rejection was -1.1% and the gate position swings of the Beck I units were within 1 to 2% of the corresponding swings with the Ontario Power units on-line. This test, and subsequent measurements, confirmed System Planning Division's simulations which indicated that the Ontario Power GS units would have limited effect on the dynamic response of the system.

2.4 Motor Starting Tests - Stelco

Prior to commencing normal operation on Stelco's Cold Roll Mill and Hot Strip Mill, a number of large synchronous motor-generator (MG) sets had to be restarted. Stelco's complement of large MG sets includes two 7500 HP (5.6 MW each) MG sets at the Cold Roll Mill, two 9800 HP (7.4 MW each) MG sets at the Hot Strip Mill and one 7500 HP MG set at the Plate Mill. The motors are started as induction machines. No detailed information was available from Stelco regarding the exact starting procedure; motors of this size are often started at reduced voltage, using an automatically switched auto transformer connection, to limit the initial reactive inrush current.

The first test involved starting two of the 7500 HP motors (the test plan called for starting only one of the motors). Figure 4 displays the recorded measurements at both Beck I GS and Gage TS. Stelco load is supplied via the 13.8 kV 'Q' bus at Gage TS fed from transformers T2 and T7. The "Q-bus" real and reactive power measurements represent the total in-feed onto the bus from the two transformers. Connection of the first motor resulted in a 23 MVAR inrush and 8.1% and 4.4% dips (peak) in the 13.8 kV and 115 kV bus voltages respectively, at Gage TS (Figure 4a). The peak voltage decline measured on the 115 kV bus at S.A. Beck GS was 2.8%, resulting in an initial increase in the reactive load of 2 to 3 MVAR on each of the Beck generators (refer to Figure 4c). The motor approached synchronous speed in under ten seconds and all voltages recovered within this period of time.

The second 7500 HP motor was connected shortly after the first, however, its protective relays tripped the unit part way through the start sequence. Several unsuccessful attempts were made to start the second motor; it was later discovered that this was due to a problem with the motor itself and was entirely unrelated to the system test or the islanded operation of the 25 Hz system.

The remaining motors were started without incident. Table 3 lists the voltage declines measured during each of the motor starts, and Figure 5 provides plots of the measurements performed during the start-up of one of the 9800 HP motors.

From Figures 5a and 5c it can be seen that there is a one-to-one correspondence between the reactive power drawn by the motor during starting and the change in the reactive power supplied from Beck I GS. Based on these measurements it appears that the reactive power requirements for motor starting at Stelco can be met in the future even when fewer Beck I units are available. There does not appear to be any need to restrict or even coordinate Stelco motor-starting operations during future islanded operation of the system.

2.5 Monitoring Customer Load Variations

The remainder of the test consisted of monitoring the system and individual unit responses to the rapid customer load variations which occur during normal operation. In particular the operation of the Stelco Hot Strip Mill was carefully monitored at Gage TS and compared with records obtained during a previous series of tests [1]. Whenever large load variations were measured at Gage TS, sets of synchronized records were also stored at Beck I GS.

Figure 6 shows one of the measurements produced during operation of the Stelco East (Strip) Mill which is supplied from the 'Q' bus at Gage TS. The Strip Mill load is cyclic and the plotted data (100 seconds) corresponds to approximately one full period (the load pattern actually repeats approximately every two minutes). From Figure 6a it can be seen that the real power load undergoes repeated 10 MW step changes superimposed on a 15 MW increase in the real load which normally lasts for up to 60 seconds. During this particular measurement period Dofasco load ('B' bus) remained constant at a low load level (2 MW + 1 MVAR). Figure 6c displays the effect of these load variations on the system frequency, 115 kV bus voltage at Beck I GS and the various unit quantities. The frequency swings resulting from the 10 MW load step changes have magnitudes on the order of 1% to 2% peak-to-peak.

Examining Figures 6e and 6f it can be seen that the wicket gates on all five units move together in response to the frequency changes which result from the Stelco load changes despite the differences in the transient droop and damping time constants between the electro-hydraulic and mechanical-hydraulic governors. The relationship between the frequency changes and the gate position changes is more clearly visible in Figure 7 where some of the variables have been plotted on the same trace. As expected, gate position swings are inverted with respect to the corresponding frequency changes. The magnitude of the individual unit gate swings, in response to the load changes, is approximately in inverse proportion to the total droop (permanent plus transient). For the three Voith governors (G1, G2, G7) a swing of 1.65% in frequency produced gate swings of between 4.5% and 5.4% corresponding to an approximate effective droop of

$$\frac{1.65}{5.0} * 100 = 33\% \quad \text{(actual setting = 30\% + 4\%)}$$

while for the two I.P. Morris governors (G6, G8) the corresponding gate swings were approximately 9% leading to a measured effective droop of

$$\frac{1.65}{9.0} * 100 = 18\% \quad \text{(actual setting = 15\% + 4\%)}$$

This provides a simple rule-of-thumb for gauging the effect of changes in the temporary droop settings on the magnitude of gate position swings in response to Stelco load variations. This could provide a simple guideline for selecting governor settings for future islanded operation with fewer Beck generators in-service, where the size of gate position and system frequency swings will become much more critical.

In an attempt to distribute the power/gate variations equally amongst the five units, the temporary droop on the Voith governors of units G1, G2 and G7 were reduced from 0.3 (30%) to 0.2 (20%) to more closely match the fixed settings on the mechanical hydraulic governors (15%). Figure 8 provides a long term (200 seconds) plot of the gate position variations with these new settings in place. Although G8 continued to have relatively larger swings in its gate position, the differences between the five units were significantly diminished.

As of April 1990, all of the 25 Hz generators at Beck I were equipped with the new Voith governors. In the future it should, therefore, be much easier to equally distribute variations in gate position and/or output power.

2.6 Summary and Recommendations - Islanded Tests

Based on the success of the system test, a one week outage of the interconnections to the 60 Hz system was scheduled, permitting necessary repairs to be performed at SAB I GS. With the permanent removal of circuit A8W and a reduction in the number of available frequency changers on the Niagara Mohawk system, the potential for future forced or planned islanded operation of the Niagara 25 Hz system has greatly increased. A number of highlights from the system test are summarized below, along with some general observations, which may be helpful in the development of future operating guidelines for the islanded system.

- Prior to disconnecting the 25 Hz system from its frequency changer interconnections, the Voith governors should be set for isolated operation with the recommended islanded settings. Current recommendations call for a temporary droop of 30% and a damping time constant of 5 seconds. In the event that a forced outage causes the system to be islanded, the Voith governors are equipped with control logic which automatically switches the governors to the isolated operation mode whenever the system frequency deviates from 25 Hz by an adjustable percentage. The initial setting of this frequency was $\pm 5\%$; based on the measured results, it appears that a setting as low as $\pm 1\%$ is advisable and should be implemented on all of the 25 Hz units. Station staff should also consider providing a remote control for isolated/network mode switching from the main

control room; currently switching between modes manually can only be accomplished at the governor cubicles.

- Entering/exiting the island using circuit BSC105 as the last/first interconnection to the 60 Hz system resulted in only minor changes in the Niagara 25 Hz system frequency and voltage. Caution will have to be exercised in the future to ensure that Niagara Mohawk frequency changers are not overloaded following the reconnection of BSC105 during large customer load variations.

- Starting Stelco's 7500 HP and 9800 HP MG sets produced voltage declines of up to 5.2% and 3.8% on the 115 kV buses at Gage TS and Sir Adam Beck I GS respectively. If necessary, these results could be extrapolated using digital simulations to project the expected voltage declines which will occur when fewer Beck I units are in-service and when the static exciters have been installed on units G1, G2 and G7. Nevertheless, based on the current measurements, it appears that it will not be necessary to place any restrictions on Stelco motor starting operations during future islanded operation of the system.

- During the entire monitoring period, with five Beck I GS units in-service and with the governor settings listed in Table 1, system frequency variations were restricted to a band of approximately 98% (24.5 Hz) to 102% (25.5 Hz) and the variations in the 115 kV bus voltage (at Beck I GS) remained between 96.5% (111 kV) and 102% (117 kV).

- The test setup focused on monitoring load variations at Stelco, however, during several monitoring periods variations due to the Dofasco arc furnace operation or Cyanamid load changes were observed. When the Dofasco arc furnace was in full operation (at the same time as Stelco load variations) on the Gage TS 'B' bus, the measured 115 kV bus voltage variations were as large as 4% peak-to-peak at Gage TS and up to 3% peak-to-peak at Beck I GS. As expected, the magnitude of the system frequency variations was not significantly affected by the arc furnace load variations. Cyanamid load changes produced significant variations in both the voltage and frequency measured at Beck I GS; additional information on the Cyanamid load should be obtained for future studies and testing.

- Prior to the test, DeCew P&C staff calibrated the underfrequency relays at Crowland and Atlas Steel. Central Region Operations staff reported that it was discovered later that the Crowland relay had been blocked for years and that Atlas Steel apparently blocked their protection prior to the system test. Based on current information, it appears that there is no longer any form of underfrequency protection on the Niagara 25 Hz system. Given the lack of physical constraints on frequency excursions it might be advisable for Operations staff to draft some guidelines outlining limits on system frequency based either on customer equipment characteristics or Ontario Hydro generating facilities.

- As expected, based on System Planning division simulations [2,3,4], the frequency/governor mode is very well damped (damping ratios as high as 0.2 were obtained in simulations). During the tests the temporary droop on the Voith governors was reduced from 30% to 20% to equalize the transient distribution of load changes among the five in-service units. This setting should be reviewed in future planning and operating studies. With fewer 25 Hz Beck I generators in-service on the system it might be advisable to consider reducing the temporary droop even further to reduce peak frequency excursions. Any improvement in frequency excursion would, however, come at the expense of increased gate motion during load changes.

3.0 GOVERNOR TESTS AND MODELLING

A program to replace all of the original I.P. Morris mechanical-hydraulic governors at Beck I was under way at the time of the system and governor tests (as of April 1990 all 25 Hz unit governors had been replaced). The governor tests were performed on the following units:

- Units G1, G2, G7 - Voith Electro-Hydraulic Governors (April 11, 1989)
- Units G6, G8 - I.P. Morris Mechanical-Hydraulic Governors (April 12, 1989)

The tests were primarily directed towards implementing the recommended governor settings for islanded operation. Additional tests were performed as required to produce detailed models of the Voith governors for use in digital simulation programs.

3.1 Voith Electro-Hydraulic Governors

The Voith electro-hydraulic governors (model EHR 530) are described in some detail in Voith product notes: T2361E and T2358E [6,7]. A block diagram representation of the governor is shown in Figure 9a. The derivative portion of the control circuitry is not shown in this figure, since it is not used on any of the units at Beck I.

Speed is measured using a toothed wheel and magnetic pick-up arrangement mounted on the turbine shaft. A single pick-up is used to produce the control signal and, therefore, a shaft run-out component is apparent in the transduced output. The run-out component does not directly affect the control dynamics of the governor as currently configured, however, it does appear continuously in the governor output signal to the moving coil pilot valve. This component may, therefore, limit the future application of a derivative gain on these units due to excessive continuous moving coil travel. According to the manufacturer's literature, the speed measurement time constant, T_n, is equal to 0.02 seconds (refer to Figure 9a).

An angle transducer which is connected at right angles to one of the main servomotor pistons provides a current signal which is linearly related to wicket gate position. This signal is

transmitted to the governor electronics where it is used as input to the permanent and temporary speed droop functions (refer to Figure 9a).

The final control error signal from the governor electronics is transmitted to a moving-coil servovalve which converts the electrical signal into a mechanical displacement of the pilot valve plunger. Through hydraulic amplifications, provided by the control valve and main gate servomotors, displacement of the pilot valve plunger results in re-positioning of the turbine wicket gates. The time constants associated with motion of the moving coil and servomotors (T_p and T_y) are included in the detailed model of Figure 9a. The effective gain between the input speed signal and gate position is lumped into one value, $1/T_g$, the governor open-loop gain.

The governor control settings, permanent droop (R_p), temporary droop (R_t), and damping time constant (T_r) are adjustable via potentiometers mounted behind the front panel of the electronic governor.

For the purposes of dynamic modelling, the Voith governor can be considered to be operating in one of the following two modes:

- network operation - intended to permit rapid loading and unloading of the unit under normal operating conditions. This mode is characterized by a short fixed damping time constant.

- isolated operation - as the name suggests, this mode is suitable for islanded or off-line operation and is characterized by an adjustable damping time constant of up to 10 seconds.

Either of the above two modes is manually selectable using pushbuttons located on the front panel of the governor. The governor will also automatically switch from network operation to isolated operation if the system frequency deviates outside of an adjustable frequency band (initially set to $\pm 5\%$). Once in the isolated mode, the governor can only be returned to network operation through manual selection, even if the frequency returns to within the desired frequency band.

The following subsections document the results of tests which were performed on Unit G2 to confirm the calibration of the adjustments of the control settings (isolated operation mode) and to determine the values of other governor parameters, such as governor open-loop gain, gate velocity limits (r_{max} and r_{min}) and moving coil time constant. The final settings established on unit G2 were also used on units G1 and G7, and a number of cursory tests were performed to verify correct operation in isolated mode for these units. Parameters and selected measurements for G1 and G7 are listed along with those for unit G2 although test records for these units have not been reproduced.

3.1.1 Static Measurements

The permanent droop potentiometer (P9) was set to 40%, corresponding to a permanent droop setting of 4%. The unit was disconnected from the system and measurements of unit frequency/speed were made as the setting of the speed reference dial was gradually increased in small steps. The unit was then synchronized to the system, and starting at zero gate position, the speed reference dial setting was once again increased in small steps until the wicket gates were fully open. The values of wicket gate position, power and speed reference setting were tabulated at each step. Table 4 lists the values obtained during both sets of measurements (for units G1, G2 and G7). Figure 10 is a plot of the incremental permanent speed droop characteristic for unit G2 obtained by combining the two sets of measurements using the common speed reference settings. The data points are plotted along with a straight line representing an exact 4% speed droop characteristic originating at exactly 25 Hz. As expected, the permanent speed droop potentiometer provides an accurate and direct setting of permanent droop.

Figure 11 is a plot of the generator power output versus wicket gate position for Unit G2. A straight line has been drawn between zero power and rated power to demonstrate that the power/gate characteristic is linear over a wide range. From this figure, no-load and full-load gate for unit G2 are taken to be 12% and 86% respectively (based on the generator rating of 45 MVA, 0.8 pf).

3.1.2 Moving Coil Response

The Voith governor has a provision for the introduction of an external speed reference signal to the governor summing junction. With the unit set at 4% permanent speed droop, a 1.09 mA signal injected at this input will produce a 100% change in gate position. To permit easy access, this input (edge connector B5 on Voith Speed Control Card, Reference Drawing 2.48-2019/5) was wired to terminal 64 on the terminal strip in each of the 25 Hz governor cubicles. This external input was used to introduce test signals for the balance of the tests.

To measure the time constant associated with the moving coil, a step disturbance corresponding to approximately 1% of speed was applied to the reference input with the units on-line, while the governor output signal and moving coil positions were monitored (refer to Figure 9a). Figure 12 shows the response of the moving coil position to the input step disturbance. The pilot valve time constant (T_p) was measured to be 45 ms which is considerably longer than the manufacturer's estimate of 15 ms. A portion of this time constant may be attributable to the measuring time constant associated with the linear-voltage-displacement transducer (LVDT) which was used in performing the measurement. Regardless, even 45 ms is a modest response time for an electromechanical device of this type and is unlikely to seriously affect the overall response of the governor control loop, especially with heavily damped settings. This measurement, along with subsequent tests, revealed that a net speed signal of +1%, appearing at the speed summing junction, is sufficient to force the moving coil to its extreme open position. A similar position limit was also encountered in the closing position. Although this effect could

be accounted for by placing limits at the moving coil output in the governor model of Figure 9a, this will not be necessary for modelling of the governor for either interconnected or islanded operating conditions.

3.1.3 Control Valve/Gate Servomotor Response

The response of the control valve and servomotor cannot be readily separated during on-site testing of the governor. Therefore, the manufacturer's estimate of 50 milliseconds was used for time constant T_y (refer to Figure 9a).

The gate servomotor time constant (T_g) was determined by examining the maximum gate velocities achieved for various magnitudes of step changes applied to the speed reference summing junction. This approach produces a reliable estimate of this time constant as long as the maximum gate velocity measurement is performed as soon as the gates begin to move, thus limiting the effect of gate feedback on the input signal [8].

Figure 13 shows one of the sets of step disturbance tests which were used to obtain the required data. Tangents have been drawn on the wicket gate position trace to indicate the portion of the curve used in determining the maximum initial gate velocity. For the large (1.3%) speed reference step changes used in these tests the maximum gate velocity limit was reached in both the opening and closing directions. As previously indicated, this magnitude of speed reference change is sufficiently large to cause the moving coil to reach its limit, particularly in the opening direction. It should also be noted that the electrical governor output signal is also on the verge of being limited at a level of just over ± 15 V.

Figure 14 is a plot of the maximum gate velocities achieved for a wide range of speed reference step disturbances. From this figure the maximum gate velocities are readily apparent: 9.7%/second in the opening direction and 14.4%/second in the closing direction. The servomotor time constant is calculated from the slope of the lower portion of each curve, prior to entering the gate velocity limit region.

$$1/T_g \text{ (open)} = 8.8 \text{ second}^{-1}$$
$$1/T_g \text{ (close)} = 14.7 \text{ second}^{-1}$$

Different values in the two directions are to be expected and have been observed in previous testing [8,9]. A time constant of 0.1 s can be used for modelling purposes, as it provides a reasonable compromise between the two measurements and coincides with the manufacturer's estimate for this value.

3.1.4 Temporary Droop/Damping Time Constant

The calibration of the temporary droop and damping time constant were determined by examination of the Speed Control circuit schematic (Voith Reference Drawing 2.48-1019/5). A simplified diagram based on this schematic is attached, as Figure 15.

The switch labelled S3/2, in Figure 15, controls the selection of the operating mode; with S3/2 closed the damping time constant is small (network operation) while with S3/2 open the damping time constant is controlled via potentiometer P15 and may be set as high as ten seconds (isolated operation).

In isolated-operation mode, the calibration of the temporary droop in terms of the position of potentiometer P12 may be determined by noting the ratio of the permanent and temporary droop summing junction input resistors (R54 and R55, respectively).

Using the established value for the permanent droop, the following equation may be used to obtain a desired temporary droop in the isolated mode

$$P12(\%) = P9(\%) * \frac{R_t^I(\%)}{R_p(\%)} * \frac{R_{55}(k\Omega)}{R_{54}(k\Omega)}$$

where $R_t^I(\%)$ = temporary droop in isolated mode
$R_p(\%)$ = permanent droop

For a temporary droop of 30% the appropriate setting is

$$P12(\%) = 40 * \frac{30}{4} * \frac{4.3}{62}$$

$$= 21\%$$

In isolated mode, the setting of potentiometer, P15 controls the damping time constant with the following calibration

$$P15(\%) = T_r^I * 10$$

where T_r^I = damping time constant in isolated mode

Therefore, a potentiometer setting of 50% was used to obtain the required time constant of 5 seconds.

Once the isolated-mode settings have been established, the corresponding network-mode values, R_t^N and T_r^N , may be calculated as follows

$$R_t^N(\%) = \frac{R_t^I(\%)}{P12(\%) * (100-P12(\%)) * 0.002 + 1}$$

$$T_r^N = [(P12(\%) * (100-P12(\%)) * 0.002 + 1] * 0.01$$

For the P12 setting of 21%, the following values of temporary droop and damping time constant are obtained when operating in the network-mode,

$$R_t^N(\%) = 30\% * 1/(21(100-21) * 0.002 + 1)$$

$$= 7\%$$

$$T_r^N(s) = (21 * (100-21) * 0.002 + 1) * 0.01$$

$$= 0.043 \text{ seconds}$$

A low value of T_r in the network-mode ensures maximum rate of response of the governor and is analogous to operating with the dashpot bypassed on a traditional mechanical-hydraulic governor. The value of T_r obtained in this particular case is unusually low and it seems unlikely that the unit would remain stable if it were unintentionally operated in an island while set for the network-mode. If necessary this problem could be overcome by replacing one or more of the fixed components on the printed circuit board (eg. resistor R67) to establish higher values of both temporary droop and damping time constant when operating in the network-mode.

3.1.5 Closed Loop Response

Linearized transfer functions for the full Voith governor representation (Figure 9a) and the simplified representation, suitable for isolated operation (Figure 9b), are derived in Appendix A. The magnitude and phase values for these two closed-loop transfer functions of the governor are plotted in Figure 16 for frequencies between 1 m Hz and 1 Hz using the following isolated mode settings:

Permanent Droop	R_p	= 0.04
Temporary Droop	R_t	= 0.3
Damping Time Constant	T_r	= 5 s
Gate Servomotor Time Constant	T_g	= 0.1 s
Moving Coil Time Constant	T_p	= 0.045 s
Control Valve Time Constant	T_y	= 0.05 s
Speed Measurement Time Constant	T_n	= 0.0 s

The measurement was performed with unit G2 set for isolated mode operation with initial values of gate position, power output and net head of 80%, 31 MW and 90 meters (295 feet) respectively. The external speed reference was modulated sinusoidally to produce gate position swings of 5% peak-to-peak over a frequency range of 2 mHz to 1 Hz. Measured points have been plotted along with the computed values in Figure 16.

Clearly, the detailed model of Figure 9a, and the parameter values provided by the manufacturer and determined through testing, provide an excellent representation of the governor dynamics for frequencies up to 1 Hz. The simplified representation of Figure 9b is adequate for most purposes although its behaviour differs somewhat from the detailed model and measured results at frequencies above 0.2 Hz.

For reference purposes, two labels have been placed on the closed-loop magnitude response corresponding to the permanent droop and total droop levels as follows:

permanent droop = 4%
magnitude (gate %/speed %) = 100/4 = 25 (28 dB)
total droop = permanent droop + temporary droop = 4% + 30%
magnitude (gate %/speed %) = 100/34 = 2.94 (9.4 dB)

As expected, for slowly varying changes (<0.001 Hz) the relationship between frequency/speed changes and gate position changes is dictated by the permanent droop setting. For a band of frequencies between 0.03 Hz and 0.4 Hz this magnitude relationship is dictated primarily by the temporary droop setting (for a value of T_r = 5 seconds). This band of frequencies encompasses the natural frequency of the prevailing governor mode (0.04 Hz) and step load changes which occur in the Stelco load with a period of approximately 10 seconds (0.1 Hz).

3.1.6 Additional Measurements on Voith Governors G1, G7

Once the detailed tests on unit G2 were complete, the settings were applied to the other two units equipped with Voith governors (G1, G7). Measurements were performed to verify the permanent speed droop setting of 4% on both of these units (refer to Table 4 for measurements). The units were configured for isolated operation (initial setting T_r = 5s, R_t = 0.3 pu) and step disturbances were applied to the speed reference summing junction. The subsequent gate responses for units G1 and G7 were compared with those obtained on unit G2 and those obtained through simulations. Figure 17 is a direct record of the response of unit G7 to a speed reference step disturbance of magnitude, 0.88%.

Figure 18 shows a simulation of the same test performed with the simplified model of Figure 9b and the isolated settings. The measured gate values of Figure 17 have been superimposed on the simulated gate results on Figure 18; the difference between measured and simulated gate position values is virtually imperceptible. The results obtained for the three Voith governor units were identical thus confirming the settings for G1 and G7.

3.2 I.P. Morris Mechanical-Hydraulic Governors

Prior to May of 1989, units G6 and G8 at Beck I GS were equipped with I.P.Morris mechanical-hydraulic governors. Since that time both governors have been replaced with Voith electro-hydraulic governors and unit G8 has been converted to 60 Hz operation. All of the tests and measurements performed on units G6 and G8 were aimed at setting the permanent and temporary droops and damping time constants to the recommended isolated operation settings, to the extent possible.

Speed measurement on these governors is performed with a flyball mechanism rotated via a long shaft and belt-drive system connected directly to the turbine/generator shaft. Changes in shaft speed or speed setting (adjusted by the Speeder motor) reposition the pilot valve stem via the floating lever. Movement of the pilot valve stem admits oil under pressure to servomotors which reposition the turbine wicket gates. Mechanical feedback between the wicket gates and the floating lever connected to the pilot valve is provided by linkages which can be adjusted mechanically to provide the necessary permanent speed droop.

The permanent droop on the two units was measured using physical reference marks placed on the speed setting wheel. The linkage adjustment was varied until the desired 4% permanent droop was achieved.

Temporary droop on these units is provided by connection to an adjustable dashpot. The dashpot could not be completely blocked and therefore, a direct measurement of the temporary droop was not possible. An estimate for this setting was obtained using two different techniques: first by measuring the relative distances between all of the pivots connecting the dashpot, gate position restoring rod, and speeder connection to the main floating lever, and second by performing measurements of the unit speed and gate position transients obtained following load rejections performed with the dashpot fully closed. These two measurements provided approximate estimates of 13% and 16% respectively for the temporary droop setting; a value of 15% was used in subsequent measurements and simulations.

The dashpot reset time, or damping time constant, is adjusted via a needle valve. On G8 the needle valve provided a wide range of adjustment, from approximately greater than five seconds with the valve set to one-quarter-turn open, to much less than one second with the valve opened greater than two turns. On G6, adjustment of the needle valve appeared to have little effect on the reset time. With the needle valve fully closed a reset time of between one and two seconds was achieved.

To confirm the overall islanded settings, the units were manually subjected to sudden changes in the speed reference setting. Figure 19 shows simulated results for both units in which measured results have been superimposed onto the simulated results obtained using the model of Figure 9b and the following parameters:

Permanent Droop (R_p)	G6, G8	0.04 pu
Temporary Droop (R_t)	G6, G8	0.15 pu
Gate Servomotor Time Constant (Tg)	G6, G8	0.2 s
Dashpot Reset Time	G6	2 s
	G8	7 s

It should be noted that the magnitude of the speed reference steps shown in these figures was not measured but rather was established based on the final gate position and the value of the permanent droop.

The approximate needle valve positions were noted and used in configuring these two governors immediately prior to the islanding test.

3.3 Governor Models and Digital Simulations

The simplified model of Figure 9b was used to simulate the gate position responses measured during the Stelco load variations. Digitally stored data corresponding to the record of system frequency in Figure 6c was used as the simulated input to the governor model for each of the units; Figure 20 provides plots of the simulated and measured gate position variations for units G1 and G6. The simulated response for unit G6 was obtained using the governor parameters listed in Section 3.2, except that the dashpot reset time was increased to 3 seconds. Similarly, a good match was obtained for the measured results for unit G8 except that the reset time had to be reduced from 7 seconds to 5 seconds. These variations in reset time are to be expected on units outfitted with dashpots particularly since the needle valve positions were reset between the time of the governor tests and the system tests.

The responses for all three Voith governor units were similar to those plotted for unit G1 in Figure 20. In each case a close match between the simulated and measured responses was only obtained if the permanent droop setting was increased from 4% to 5.5%. No reason for this discrepancy was uncovered and a permanent droop value of 4% should be used in any further simulations of these units since this value was confirmed via several different measurements.

3.3.1 Parameters for Digital Representation

The "HYGOV" model of the PTI Power System Simulator package and the "TYPE 10" model of the TSSIMU program are two commonly used digital hydraulic governor models. The "TYPE 10" model is intended to represent governors which utilize gate feedback to provide speed droop, and is similar in form to the governor models of Figures 9a and 9b. Tables 5a and 5b summarize the "TYPE 10" parameters which can be used in modelling the isolated-mode operation of Beck I units G1, G2 and G7. Parameters for the I.P. Morris governors (units G6

and G8) have not been included since they have been replaced by new governors and G8 is now on the 60 Hz system. It may be assumed that the parameters for unit G6 will be similar to the values listed in Table 5a.

The "HYGOV" model is intended for use with governors which employ pilot servomotor feedback to provide speed droop. For isolated-mode operation, "HYGOV" parameters may be selected to provide a reasonable approximation of the dynamics of governors which employ gate-position feedback. Appropriate "HYGOV" parameters for modelling of isolated-mode operation of the Voith governor units have been included in Table 5.

3.4 Summary and Recommendations - Governor Tests

The tests performed on the Voith electro-hydraulic governors confirmed that these units allow for extremely accurate control of the droop settings and damping time constant. The potentiometer settings corresponding to specific parameter values have been verified, allowing for easy modification of governor settings based on future recommendations from either the System Planning Division or the Power System Operations Division. Detailed models suitable for simulating the performance of these governors during isolated-mode operation have been provided. Simple digital simulations performed using these models have demonstrated that they accurately portray the actual performance of the units during on-line operation.

The external speed reference input of each of the newly installed Voith governors should be wired to the terminal strip to permit easy access. This input is extremely useful for testing of the governor and in the future could be used in conjunction with a centralized controller to implement auxiliary plant control functions.

When operating in network mode the temporary droop reset time is extremely low and is not directly adjustable. The minimum acceptable setting for this parameter should be determined via detailed simulations and, if necessary, modifications should be made to the fixed components which control this reset time.

4.0 ACKNOWLEDGMENTS

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TABLE 1

INITIAL GOVERNOR SETTINGS - ISOLATED OPERATION

Unit/Governor	Permanant Speed Droop (pu speed/pu gate)	Temporary Speed Droop (pu speed/pu gate)	Damping Time Constant (seconds)
G1 (Voith, Electro-Hydraulic)	0.04	- 0.30	5.0
G2 (Voith, Electro-Hydraulic)	0.04	0.30	5.0
G6 (I.P. Morris, Mechanical Hydraulic)	0.04	0.15	2.0
G7 (Voith, Electro-Hydraulic)	0.04	0.30	5.0
G8 (I.P. Morris, Mechanical Hydraulic)	0.04	0.15	5.0

TABLE 2

INSTRUMENTATION LIST - SYSTEM TEST

QUANTITIES	LOCATION	DESCRIPTION/TRANSDUCER
Bus Voltage (115 kV)	S.A. Beck I GS	Station Phase-to-Phase Transducer (Woodex)
System Frequency (25 Hz)	S.A. Beck I GS	Custom Frequency Transducer (Research)
Real Power Output (Units G1, G2)	S.A. Beck I GS	Station Watt Transducers (Woodex)
Real Power Output (Units G6, G7, G8)	S.A. Beck I GS	Custom Three-Phase Watt Transducer (Research)
Reactive Power Output (Units G1, G2, G6, G7, G8)	S.A. Beck I GS	Station Var Transducers (Woodex)
Wicket Gate Position (Units G1, G2, G7)	S.A. Beck I GS	Governor Electronic Gate Feedback Signal (Voith)
Wicket Gate Position (Units G6, G8)	S.A. Beck I GS	Custom Linear Slidewire (Research)
Shaft Speed (Units G1, G2, G7)	S.A. Beck I GS	Governor Electronic Speed Signal (Voith)
Governor Moving Coil Position (Unit G2)	S.A. Beck I GS	Custom Linear Displacement Voltage Transducer (Research)
Bus voltage (115 kV)	Gage TS	Custom Three-Phase Transducer (Research)
'B' & 'Q' Bus voltages[1] (13.8 kV)	Gage TS	Custom Three-Phase Transducers (Research)
'B' & 'Q' Bus Real Power Load	Gage TS	Custom Three-Phase Transducer and Summing Network fed from T1, T2 and T7 PTs and CTs (Research)
'B' & 'Q' Bus Reactive Load	Gage TS	Custom Three-Phase Transducers, Phase Shifters and Summing Network fed from T1, T2 and T7 PTs and CTs (Research)

Notes: (1) 'B' bus supplies Dofasco load via transformer T1
'Q' bus supplies Stelco load via transformers T2, T7

TABLE 3

25 Hz SYSTEM VOLTAGE DECLINE MEASUREMENTS
STELCO MOTOR STARTING

Stelco Motor Start	Gage TS 'Q' Bus (13.8 kV) Voltage Decline	Gage TS (115 kV) Voltage Decline	S.A. Beck I GS (115 kV) Voltage Decline
7500 HP (#1)	8.1%	4.4%	2.8%
7500 HP (#3)	7.8%	4.6%	3.4%
9800 HP (#1)	8.0%	4.6%	3.4%
9800 HP (#2)	9.0%	5.2%	3.8%

TABLE 4
STATIC SPEED DROOP MEASUREMENT
SIR ADAM BECK I GS, UNITS G1, G2, G7[1]

SPEED REFERENCE DIAL SETTING	OFF-LINE FREQUENCY[2]			ON-LINE GATE POSITION[2] (%)			ON-LINE REAL POWER[2] (MW)		
	G1	G2	G7	G1	G2	G7	G1	G2	G7
60	25.02	24.99	25.03	8.6	4.8	1.0	0.0	-0.4	-2.9
62	-	25.08	-	-	13.9	-	-	1.2	-
64	25.22	25.22	25.23	34.2	25.3	27.9	11.2	5.8	13.0
66	-	25.32	-	-	36.7	-	-	11.7	-
68	25.44	25.44	25.50	56.2	47.6	50.5	22.3	17.3	27.4
70	-	25.56	-	-	57.3	-	-	21.6	-
72	25.67	25.68	25.68	78.1	70.0	72.5	32.4	28.8	36.0
74	-	25.75	-	-	80.3	-	-	33.1	-
76	25.88	25.87	25.87	99.7	91.9	94.2	39.0	37.4	41.8
78	-	25.96	-	-	100.0	-	-	38.9	-

NOTES:

1) Unit Ratings: G1, G2: 45 MVA, 0.8 pf, 187.5 RPM
G7: 54 MVA, 0.8 pf, 187.5 RPM

Net Head during measurements: G1 (89.8m), G2 (89.6m), G7 (88.3m)

2) Frequency - Custom three-phase frequency transducer
Gate Position - Voith gate position transducer
Output Power - Station Woodex dc current-loop watt transducer

TABLE 5A
"TYPE 10" AND "HYGOV" MODEL PARAMETERS FOR ISOLATED-OPERATION MODE
S.A. BECK I GS, UNIT G2

Description	Type 10[1]	HYGOV[1]
Servo System Gain (seconds^{-1})	$Q = 10$	-
Servo System Time Constant[2]	-	$T_g = 0.5$
Turbine Gain (pu)[3]	-	$A_t = 1.11$
Permanent Droop (pu)	$R_p = 0.04$	$R = 0.04$
Temporary Droop (pu)[4]	$R_t = 0.2$	$r = 0.2$
Dashpot Reset Time (seconds)	$T_r = 5$	-
Full Load Gate (pu)	$G_{FL} = 0.86$	-
No-Load Gate/No-Load Flow (pu)	$G_{NL} = 0.14$	$Q_{NL} = 0.14$
Maximum Gate Limit (pu)	-	$G_{MAX} = 1$
Minimum Gate Limit (pu)	-	$G_{MIN} = 0$
Maximum Gate Opening Velocity (pu/s)	R_{MAX} (open) = 0.1	$R_{LIM} = \pm(0.1 + 0.14)/2$
Maximum Gate Closing Velocity (pu/s)	R_{MAX} (close) = 0.14	$R_{LIM} = \pm(0.1 + 0.14)/2$
Deadband Magnitude	negligible	negligible
Power at Full Load Gate (pu on Gen. MVA Base)	$P_{MAX} = 0.8$	-

[1]Blank fields indicate parameters not included in this model

[2]Due to the differences between models this variable is related to, but not the same as, the gate servomotor time constant which appears elsewhere in this report

[3]$A_t = P_{MAX}/(G_{FL}-G_{NL})$, lumps the effective gain introduced by gate values expressed in real gate opening, and unit output expressed on the generator MVA base

[4]As left setting for temporary droop (0.20 pu)

TABLE 5B
"TYPE 10" AND "HYGOV" MODEL PARAMETERS FOR
ISOLATED-OPERATION MODE VOITH GOVERNORS, S.A. BECK I GS, UNITS G1, G7

All parameters identical to unit G2 (Table 5a) with the exception of:

	G1		G7	
	TYPE 10	HYGOV	TYPE 10	HYGOV
Full Load Gate (pu)	0.85	-	0.84	-
No-Load Gate/Flow (pu)	0.10	0.10	0.06	0.06
Turbine Gain (pu)	-	1.07	-	1.03

APPENDIX A
DERIVATION OF EQUIVALENT TRANSFER FUNCTION VOITH ELECTRO-HYDRAULIC GOVERNOR

Referring to the governor block diagram of Figure 9 and defining

$$G(s)=\frac{1}{1+sT_p} * \frac{1/T_g}{1+sT_y} * \frac{1}{s} \qquad \text{(A-1)}$$

$$H(s) = R_p + \frac{R_t\ s\ T_r}{1+\ s\ T_r} \qquad \text{(A-2)}$$

The closed loop gate-position/speed transfer function is given by

$$\frac{g(s)}{n(s)} = \frac{1}{1 + sT_n}\ \frac{G(s)}{1 + G(s)\ H(s)}$$

$$= \frac{(1/R_p) * (1+sT_r)}{(T_4\ s^4 + T_3\ s^3 + T_2\ s^2 + T_1\ s + 1)(1 + sT_n)} \qquad \text{(A-3)}$$

where

$$T_4 = T_r\ T_y\ T_p\ T_g/R_p$$

$$T_3 = T_g(T_r\ T_p + T_p\ T_y + T_r\ T_y)/R_p$$

$$T_2 = T_g(T_r + T_p + T_y)/R_p$$

$$T_1 = (1 + R_t/R_p)T_r + T_g/R_p$$

For the range of gains and time constants associated with isolated operation of the Voith governor,

$T_r > T_g > T_y, T_p, T_n$

Based on the above

$$T_2 > T_3 > T_4$$

The denominator of Equation A-3 can be approximated by the following second - order terms,

$$\frac{g(s)}{n(s)} = \frac{(1/R_p)\,(1+sT_r)}{T_g\,T_r\,s^2/R_p + [T_g + T_r(R_t + R_p)]\,s/R_p + 1} \qquad \text{(A-4)}$$

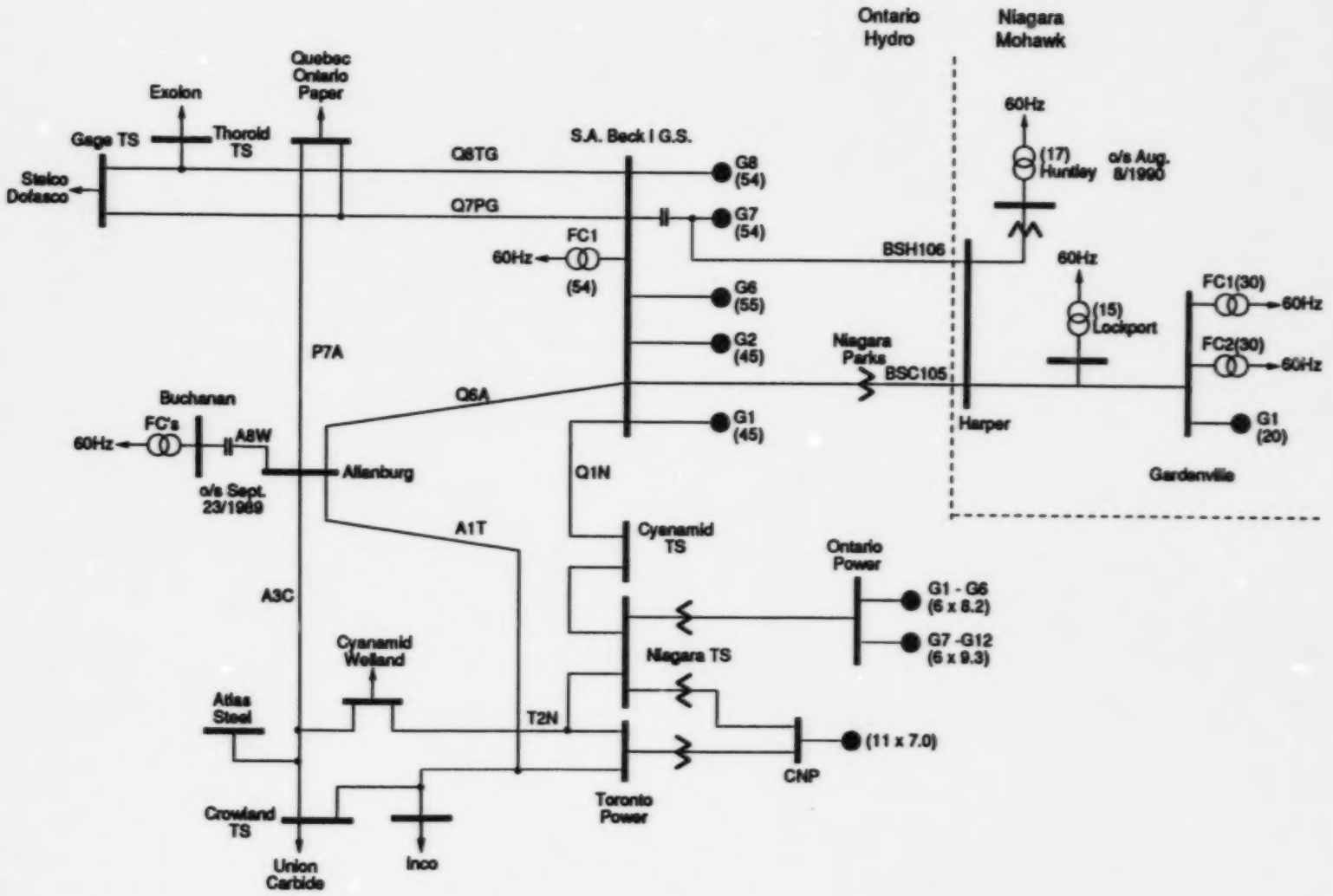
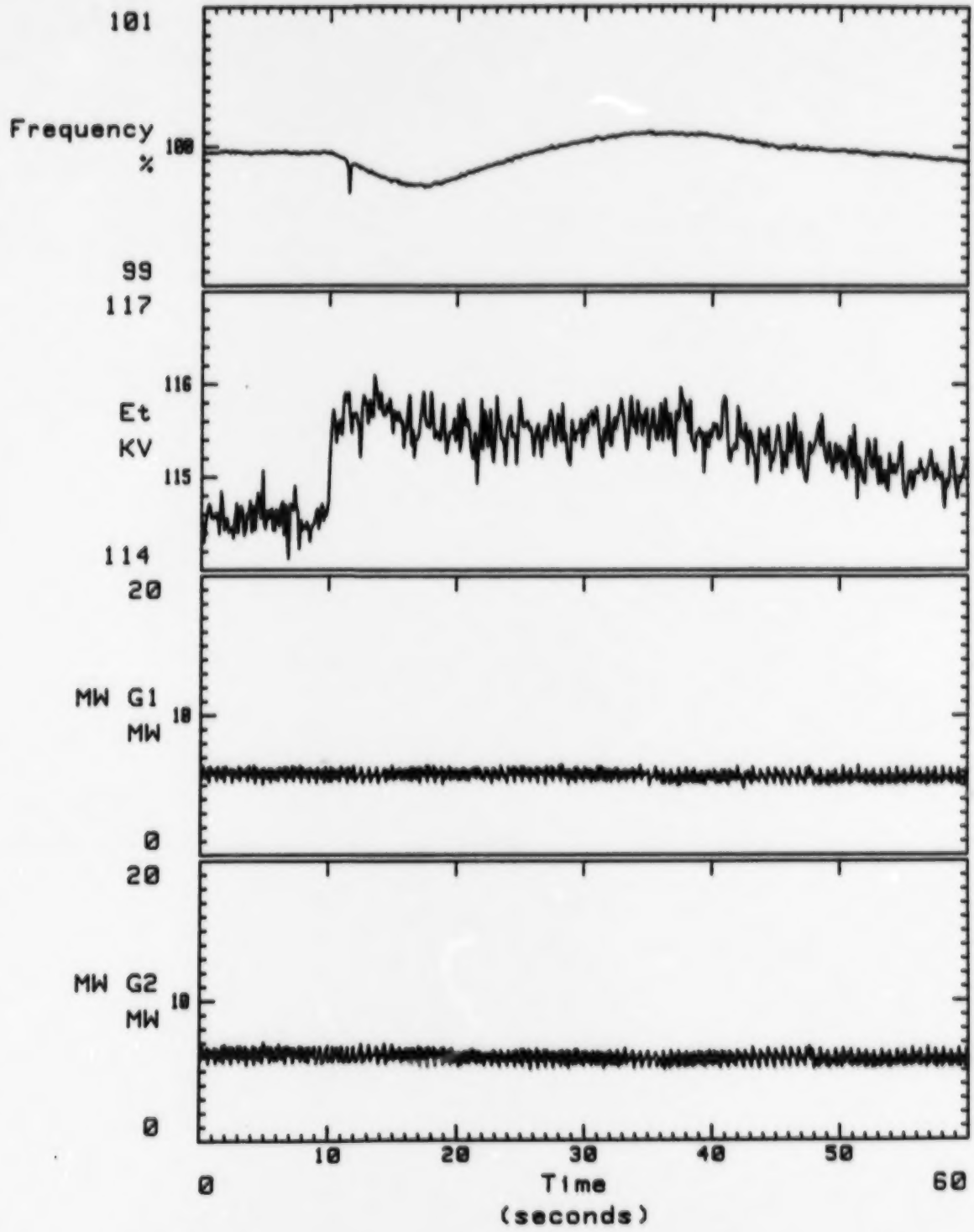


FIGURE 1

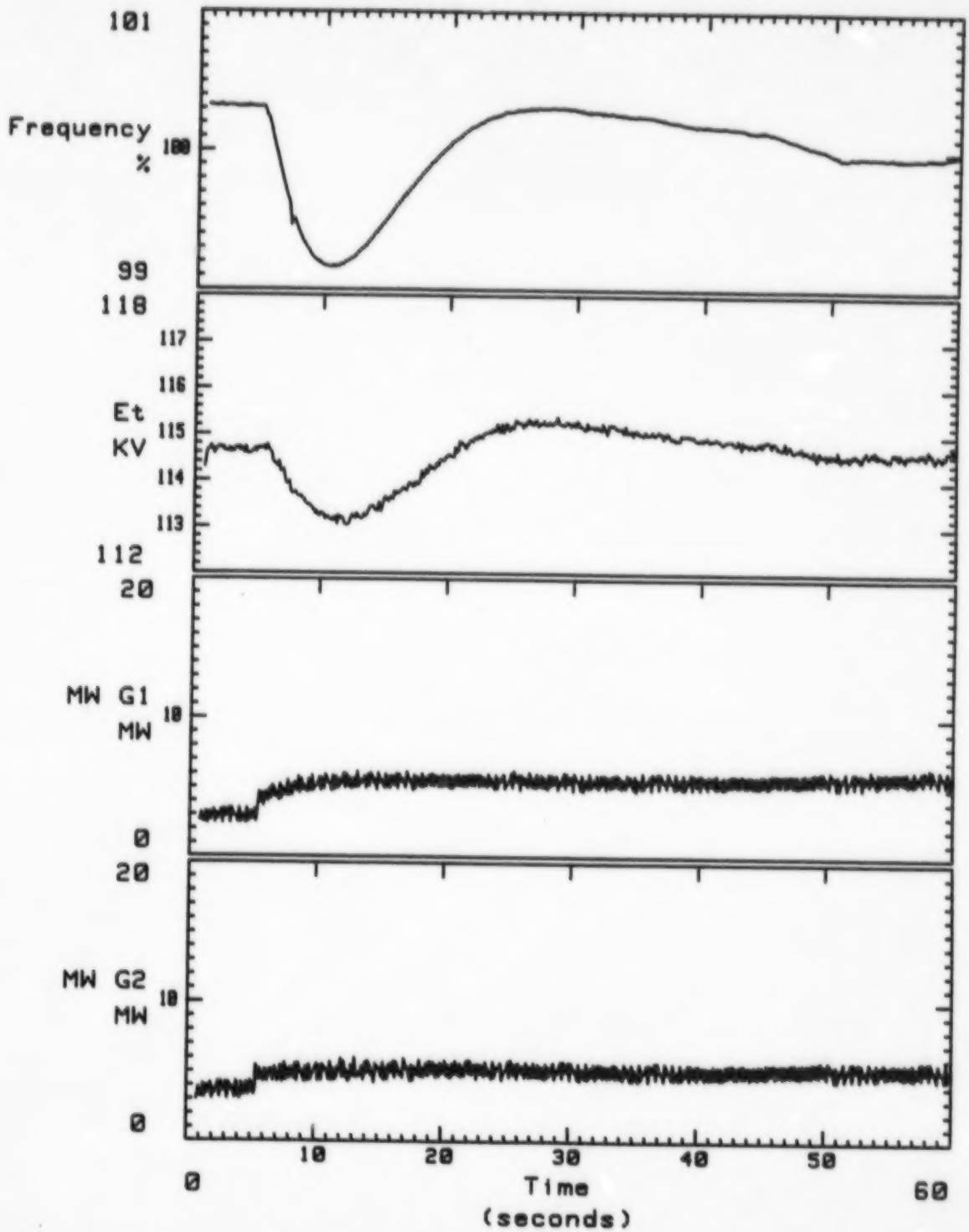
NIAGARA 25 Hz SYSTEM SCHEMATIC (EARLY - 1989)

18404-GE-RD



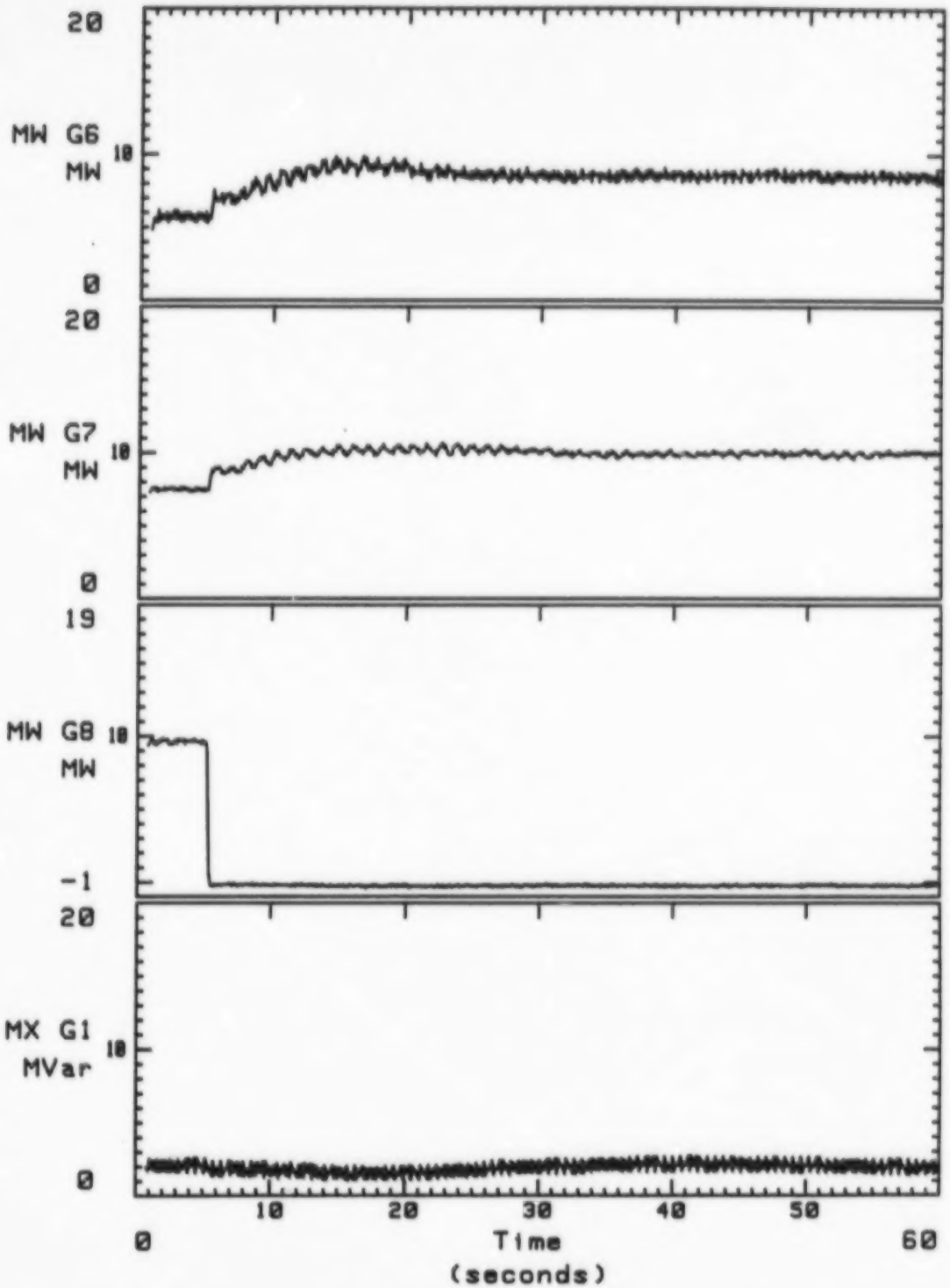
Niagara 25 Hz System Test A3
16 Apr 1989 @ 11:28:20

FIGURE 2: ENTERING ISLAND BY OPENING CIRCUIT BSC105 [31] [90-309]



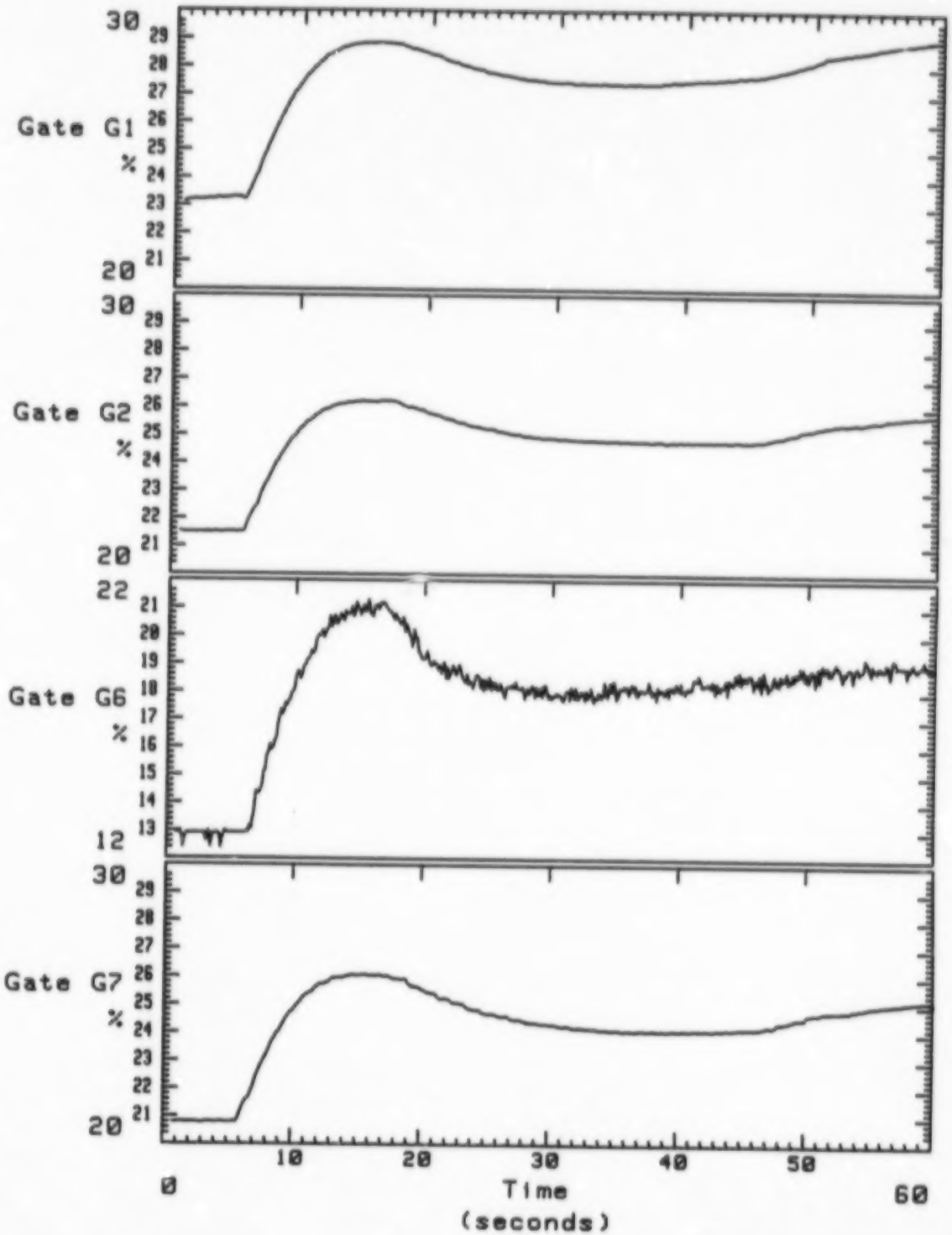
Niagara 25 Hz System Test A5
16 Apr 1989 @ 11:38:50

FIGURE 3a: REJECTION OF BECK$_{32}$ I UNIT G8 FROM 10 MW 90-309



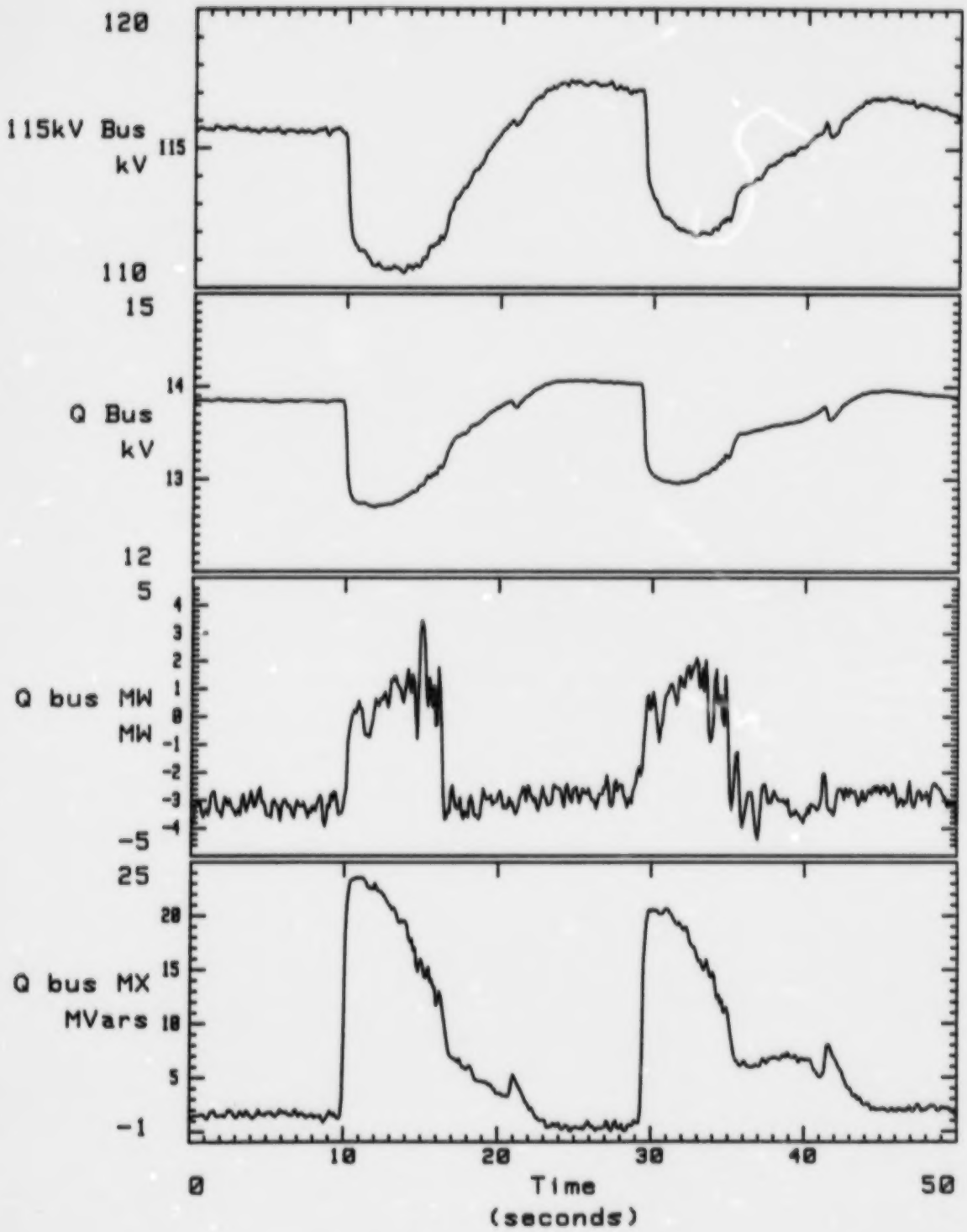
Niagara 25 Hz System Test A5
16 Apr 1989 @ 11:38:50

FIGURE 3b: REJECTION OF BECK I UNIT G8 FROM 10 MW



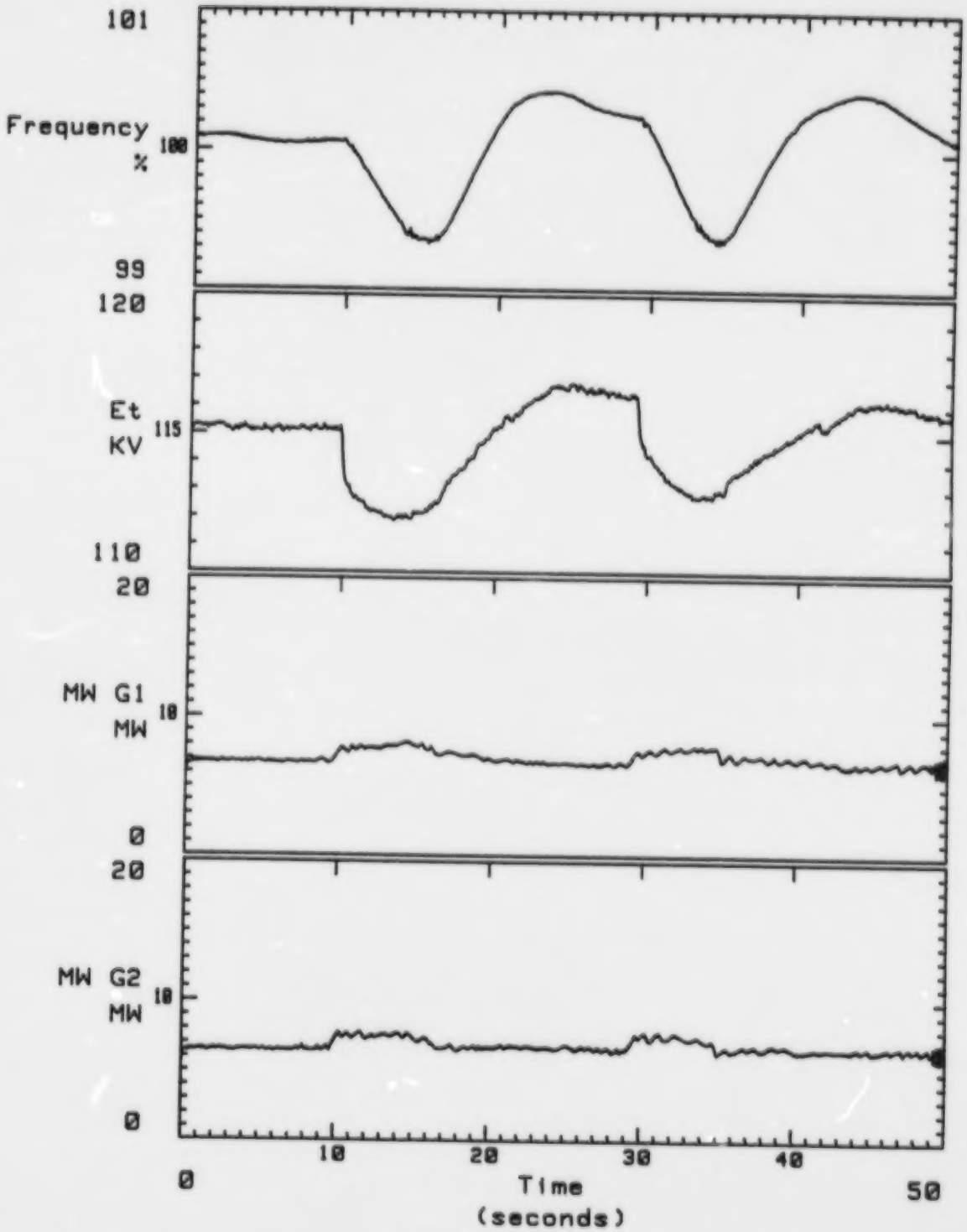
Niagara 25 Hz System Test A5
16 Apr 1989 @ 11:38:50

FIGURE 3c: REJECTION OF BECK I UNIT G8 FROM 10 MW



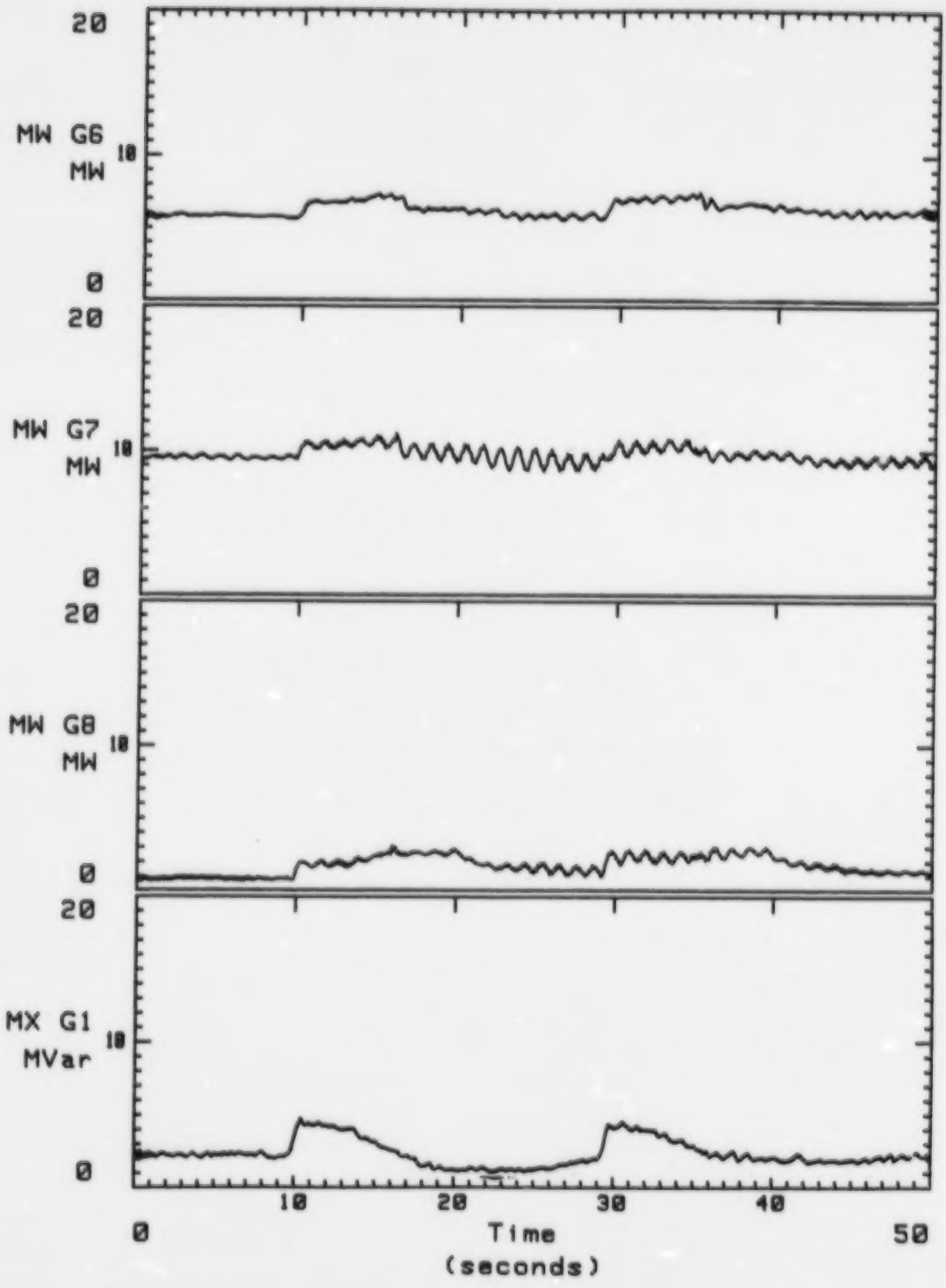
Gage TS Test A9
16 Apr 1989 @ 15:29:00

FIGURE 4a: MOTOR STARTING TEST (STELCO 7500 HP)
GAGE TS MEASUREMENTS



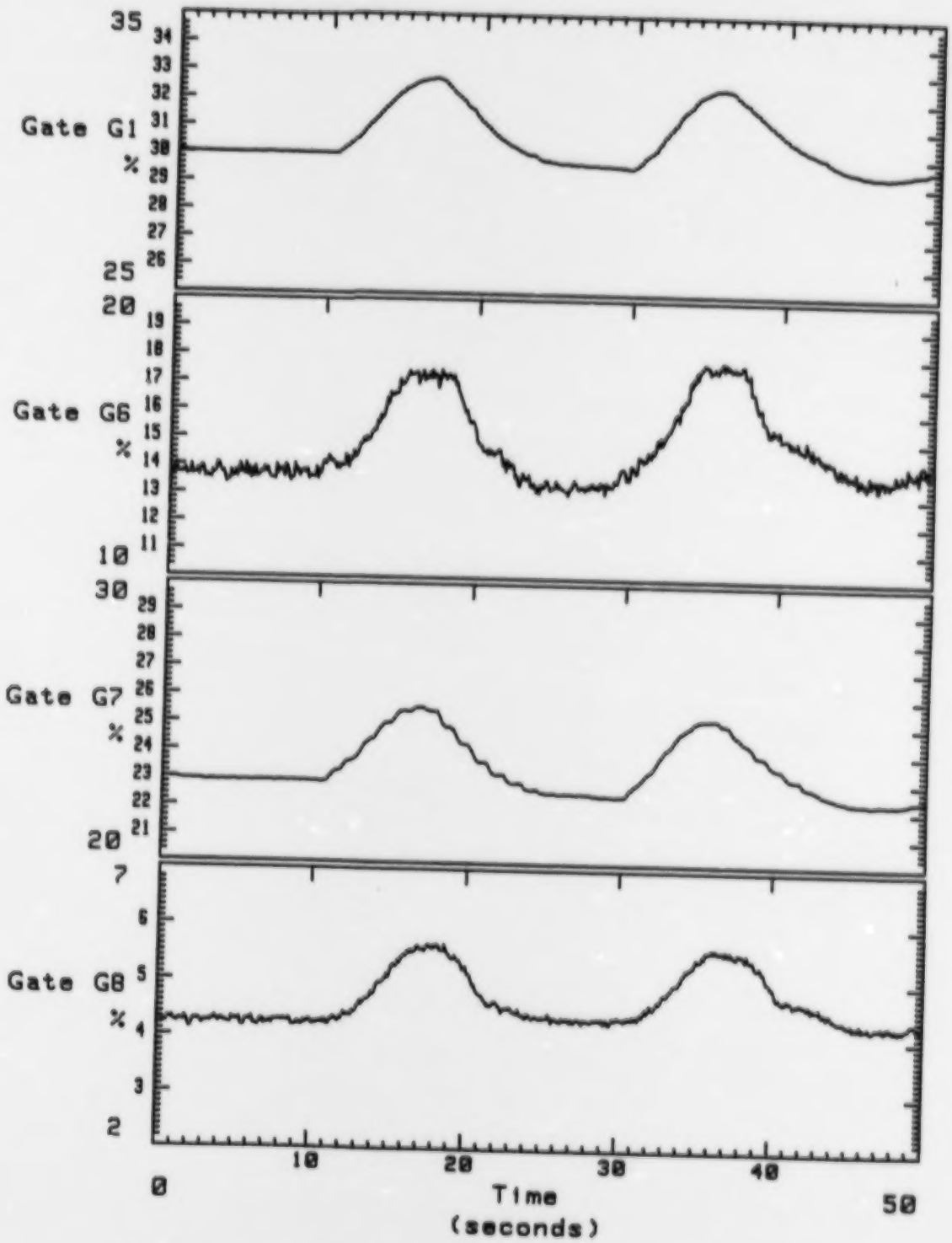
Niagara 25 Hz System Test A9
16 Apr 1989 @ 15:29:00

FIGURE 4b: MOTOR STARTING TEST (STELCO 7500 HP)
BECK I GS MEASUREMENTS



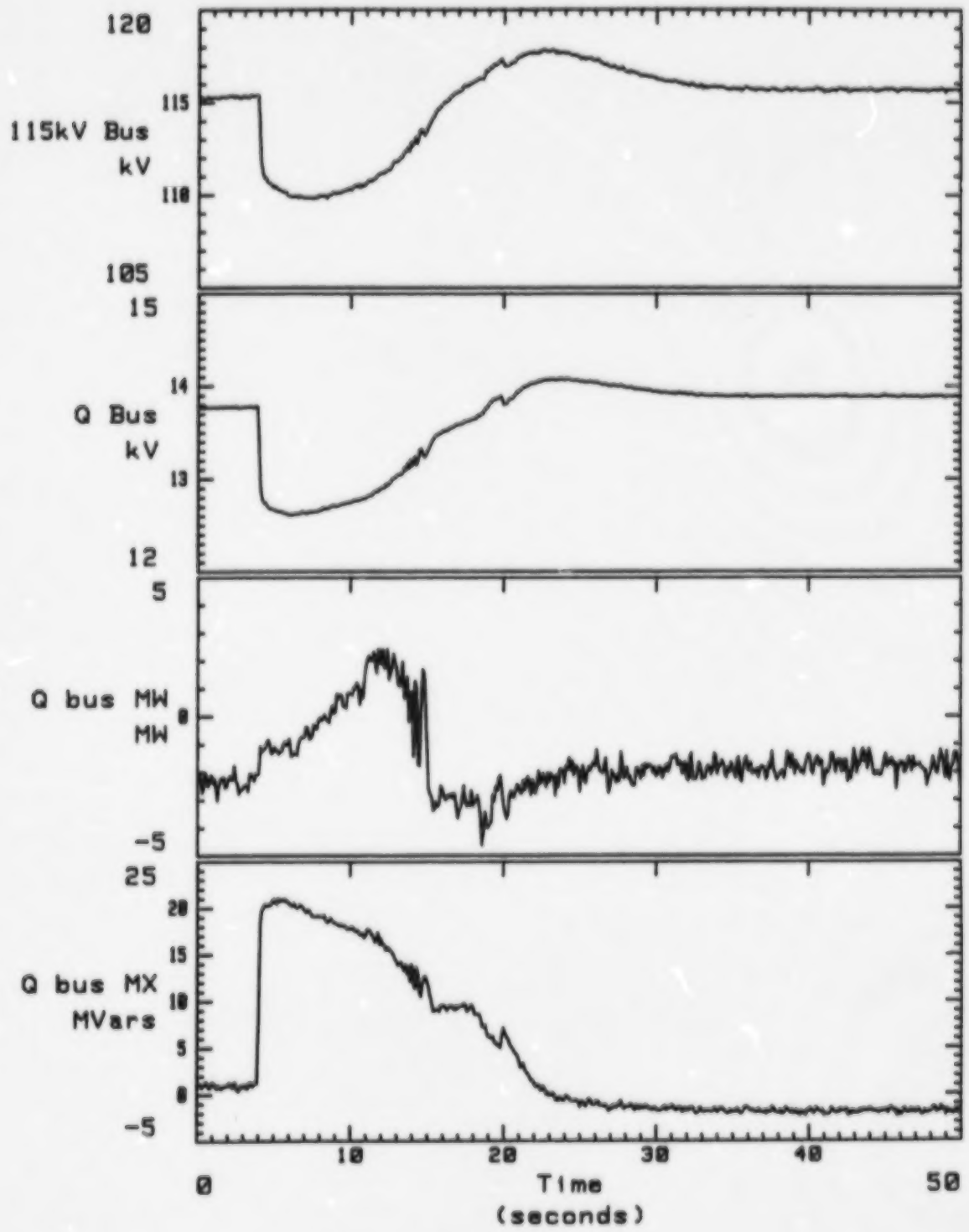
Niagara 25 Hz System Test A9
16 Apr 1989 @ 15:29:00

FIGURE 4c: MOTOR STARTING TEST (STELCO 7500 HP)
BECK I GS MEASUREMENTS



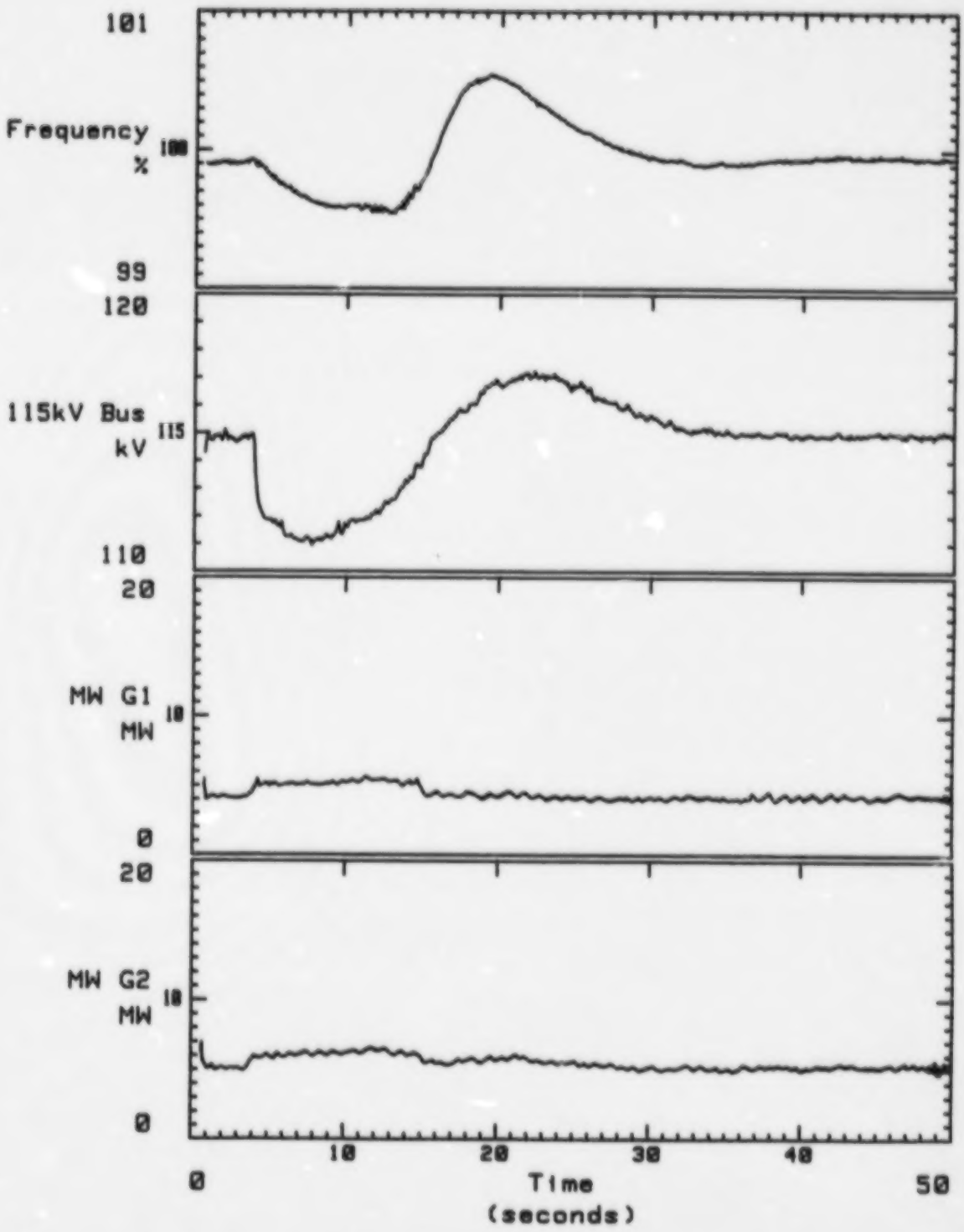
Niagara 25 Hz System Test A9
16 Apr 1989 @ 15:29:00

FIGURE 4d: MOTOR STARTING TEST (STELCO 7500 HP)
BECK I GS MEASUREMENTS



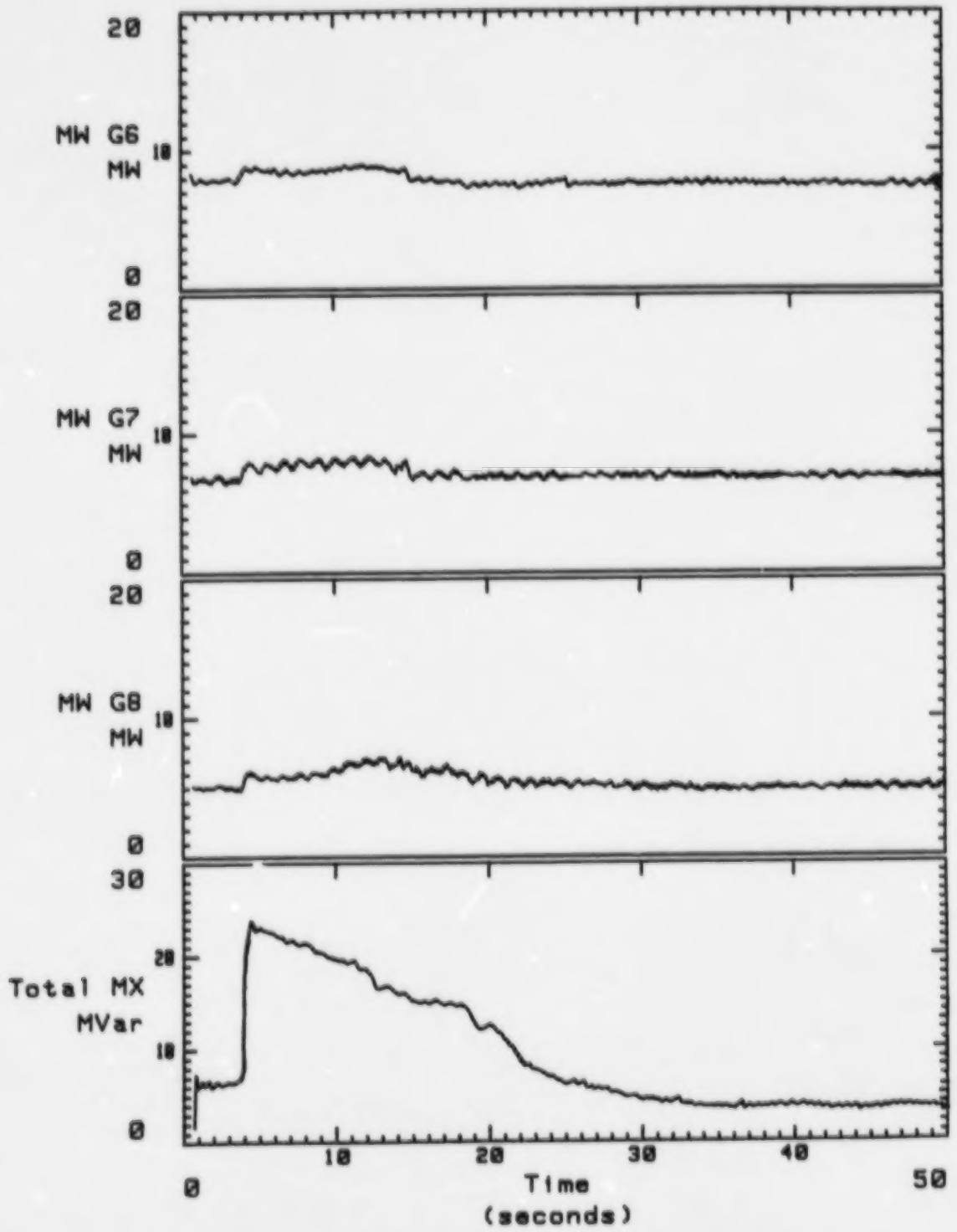
Gage TS Test A17
16 Apr 1989 @ 21:00:00

FIGURE 5a: MOTOR STARTING TEST (STELCO 9800 HP)
GAGE TS MEASUREMENTS



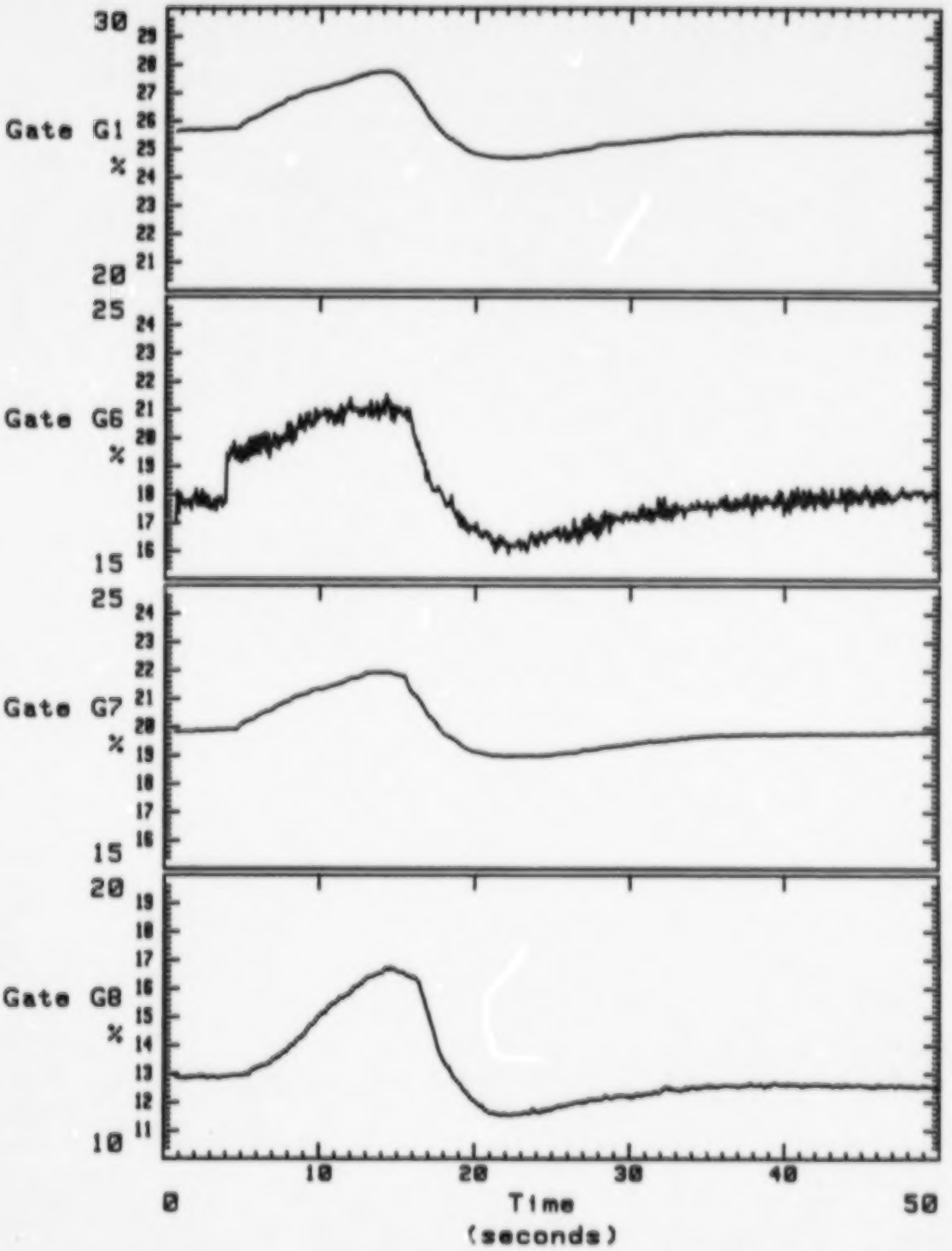
Niagara 25 Hz System Test A17
16 Apr 1989 @ 21:00:00

FIGURE 5b: MOTOR STARTING TEST (STELCO 9800 HP)
BECK I GS MEASUREMENTS



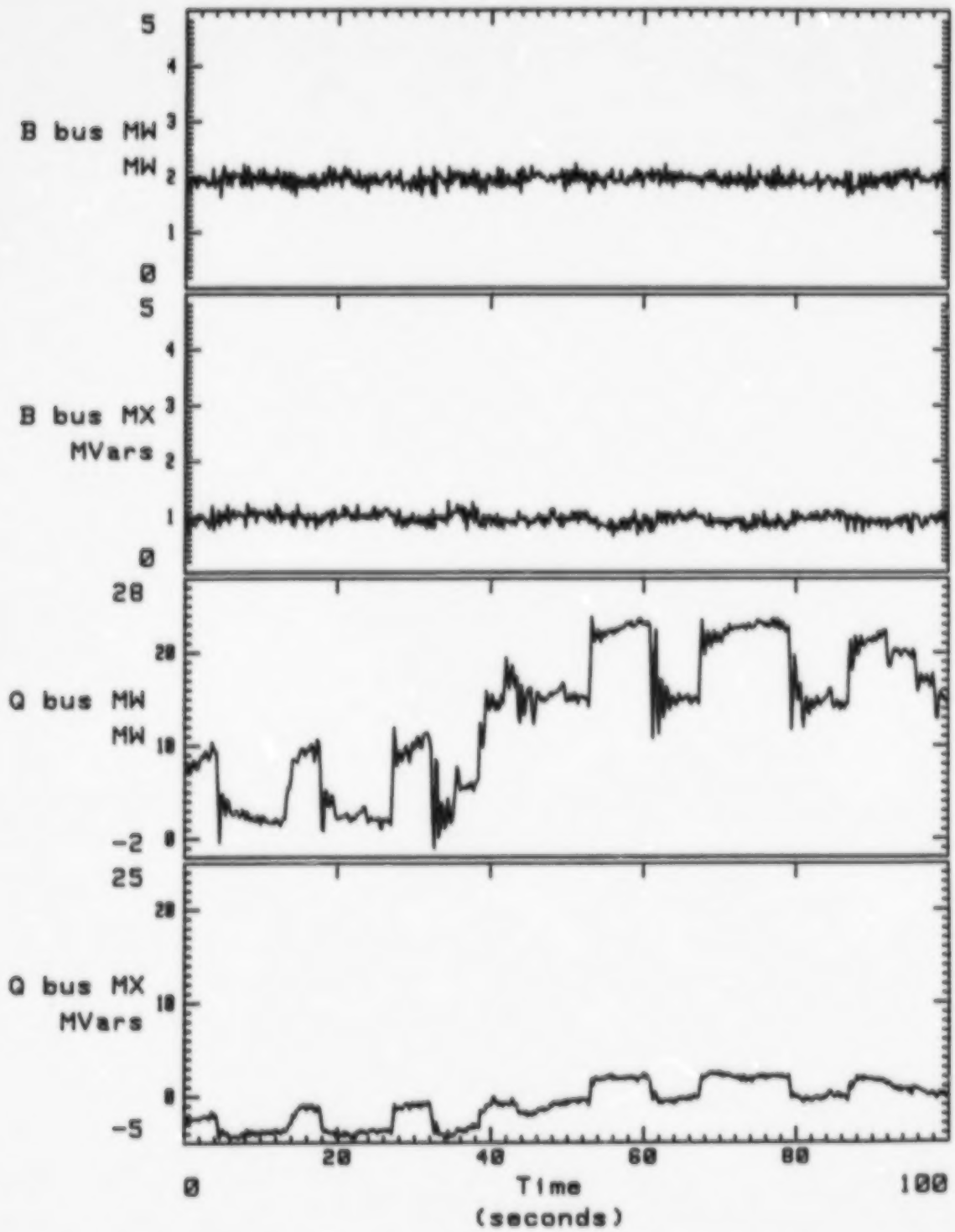
Niagara 25 Hz System Test A17
16 Apr 1989 @ 21:00:00

FIGURE 5c: MOTOR STARTING TEST (STELCO 9800 HP)
BECK I GS MEASUREMENTS



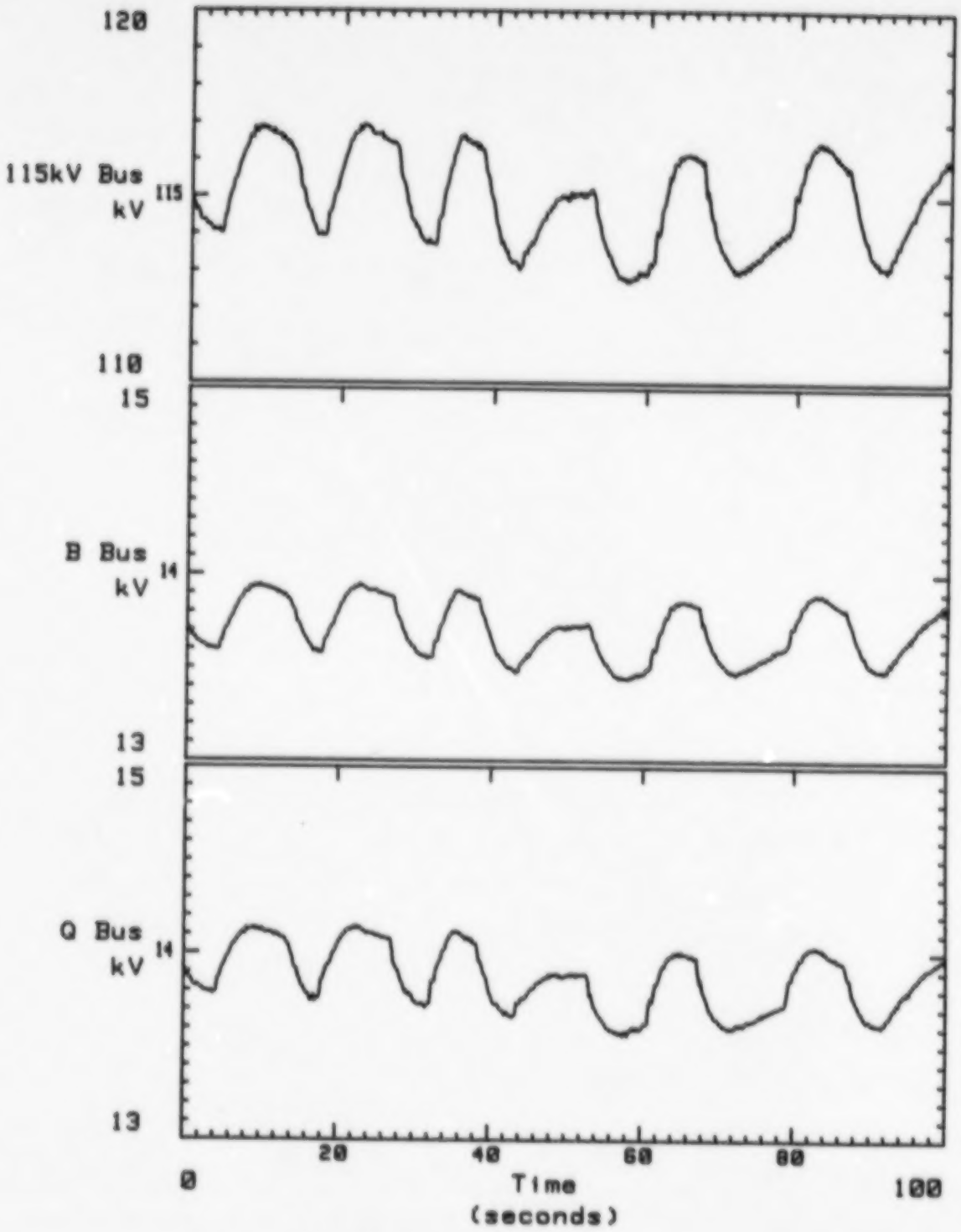
Niagara 25 Hz System Test A17
16 Apr 1989 @ 21:00:00

FIGURE 5d: MOTOR STARTING TEST (STELCO 9800 HP)
BECK I GS MEASUREMENTS



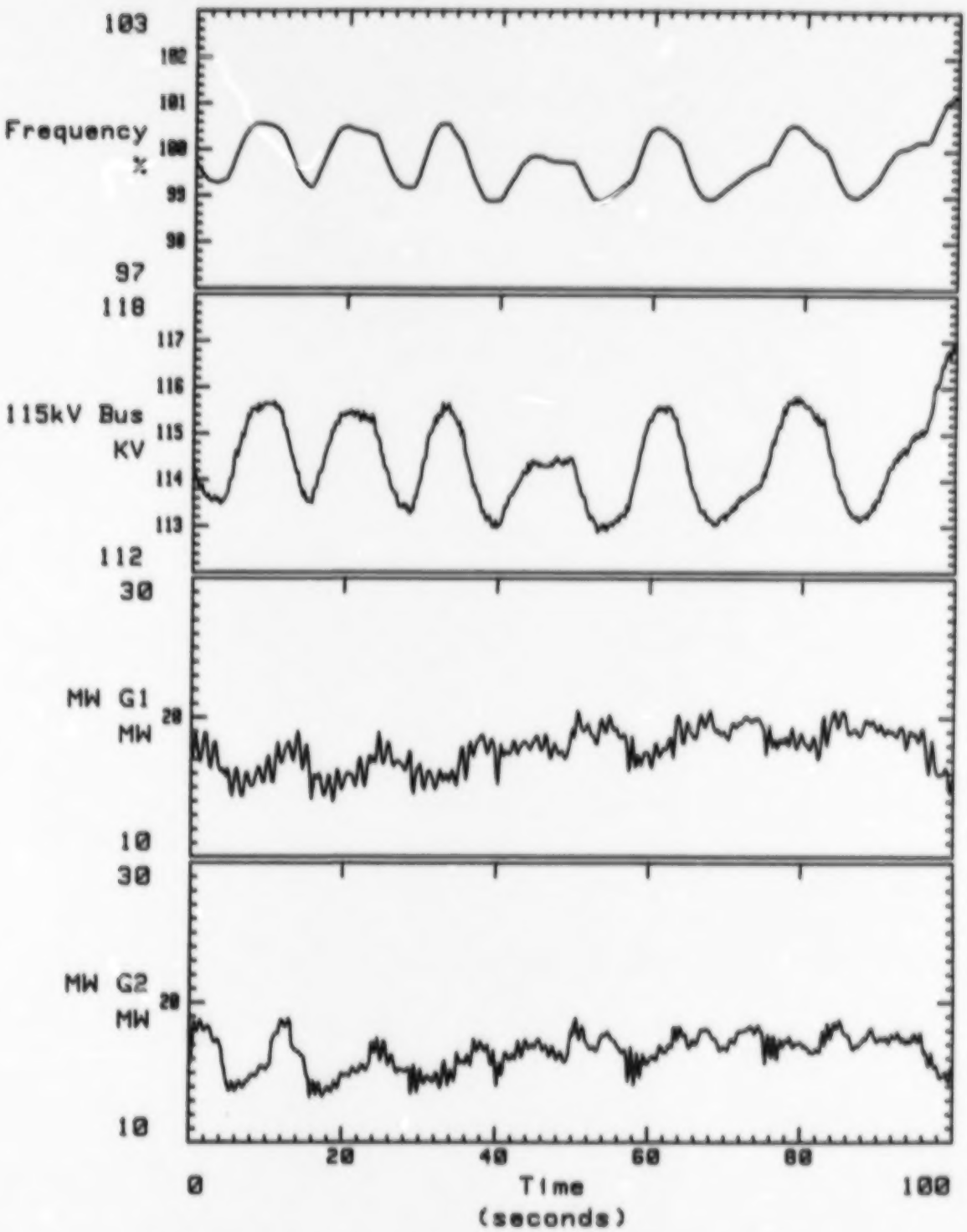
Gage TS Test C2
17 Apr 1989 @ 06:25:00

FIGURE 6a: STELCO EAST (STRIP) MILL LOAD VARIATIONS
GAGE TS MEASUREMENTS



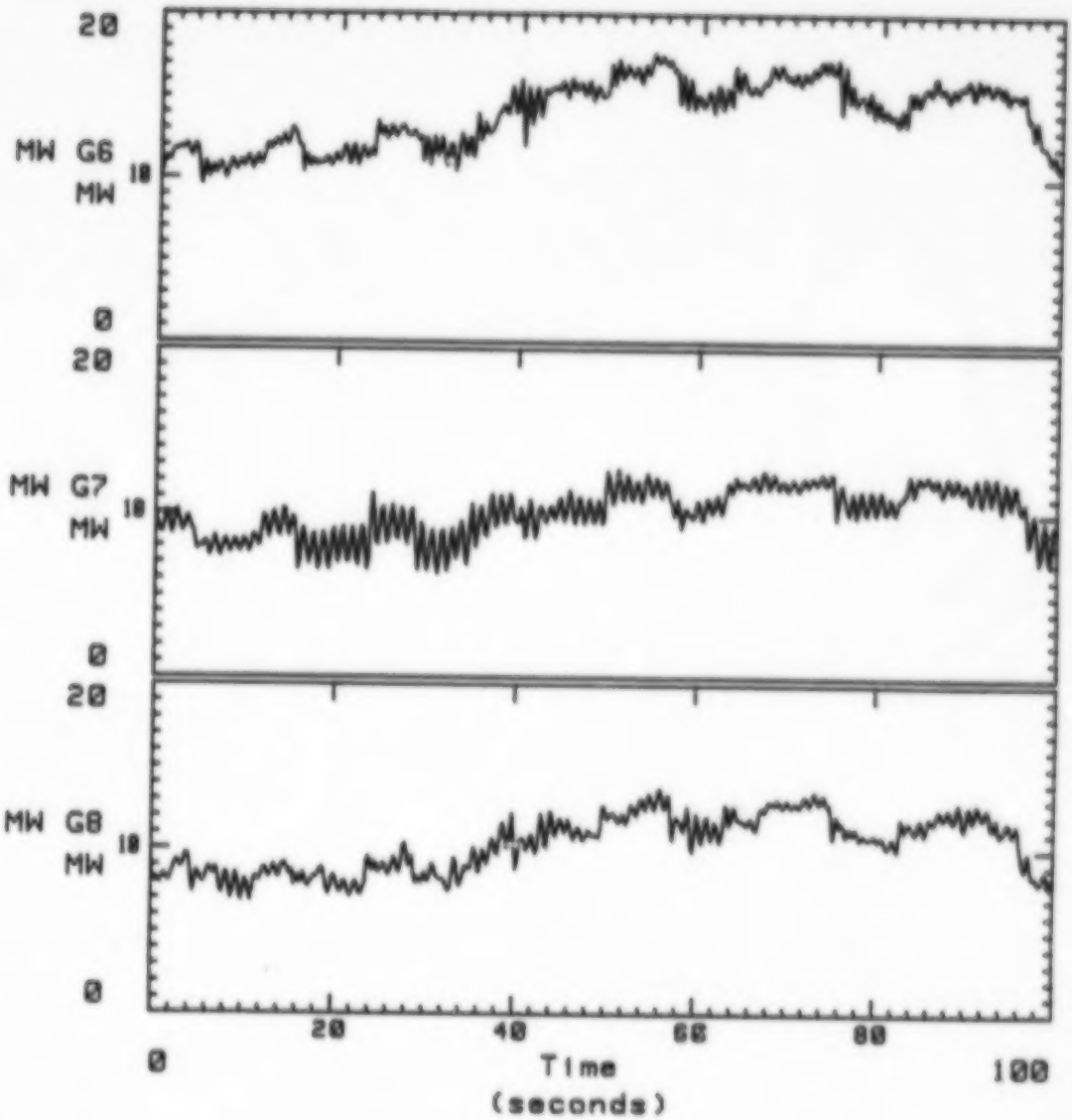
Gage TS Test C2
17 Apr 1989 @ 06:25:00

FIGURE 6b: STELCO EAST (STRIP) MILL LOAD VARIATIONS
GAGE TS MEASUREMENTS



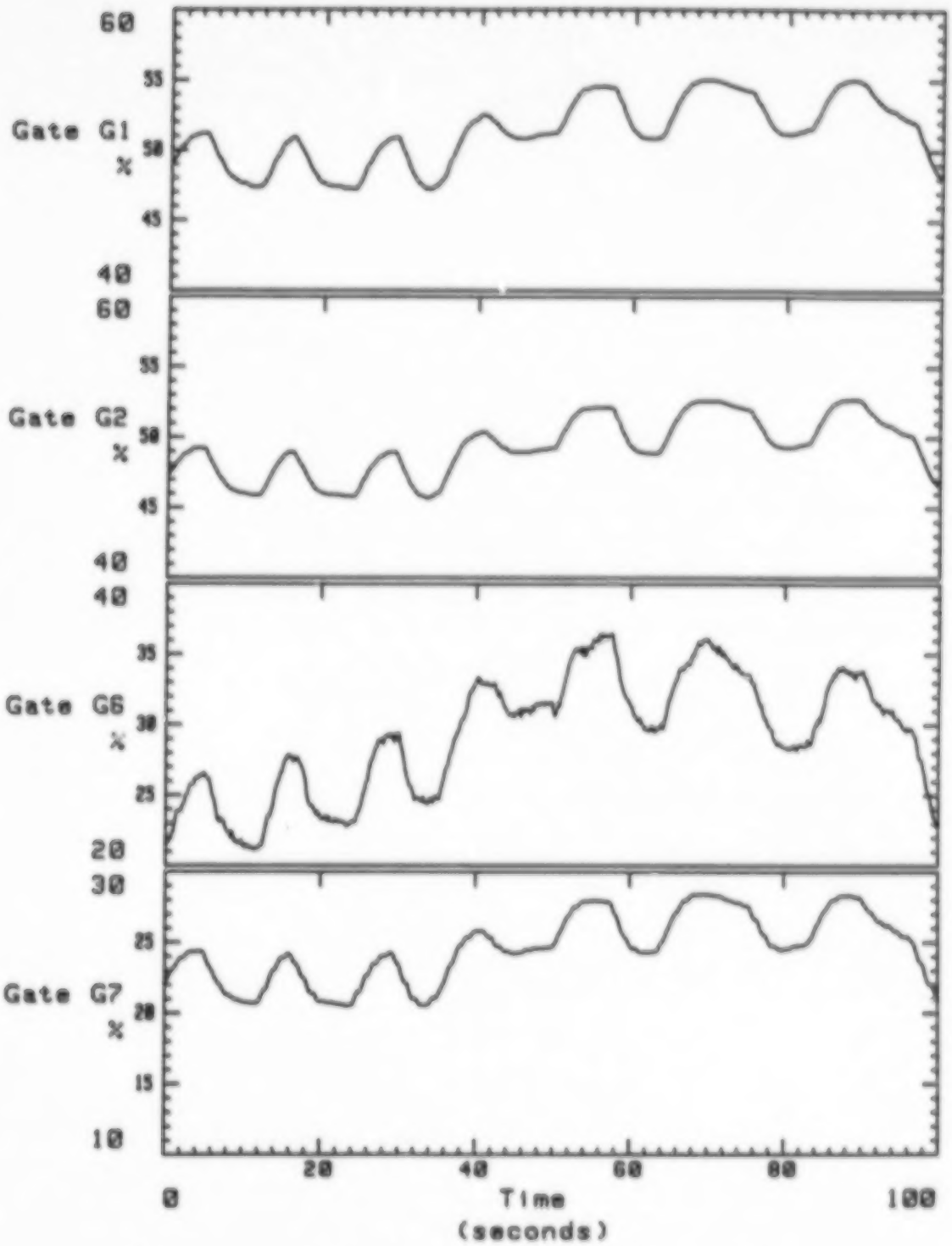
Niagara 25 Hz System Test C2
17 Apr 1989 @ 06:25:00

FIGURE 6c: STELCO EAST (STRIP) MILL LOAD VARIATIONS
BECK I GS MEASUREMENTS



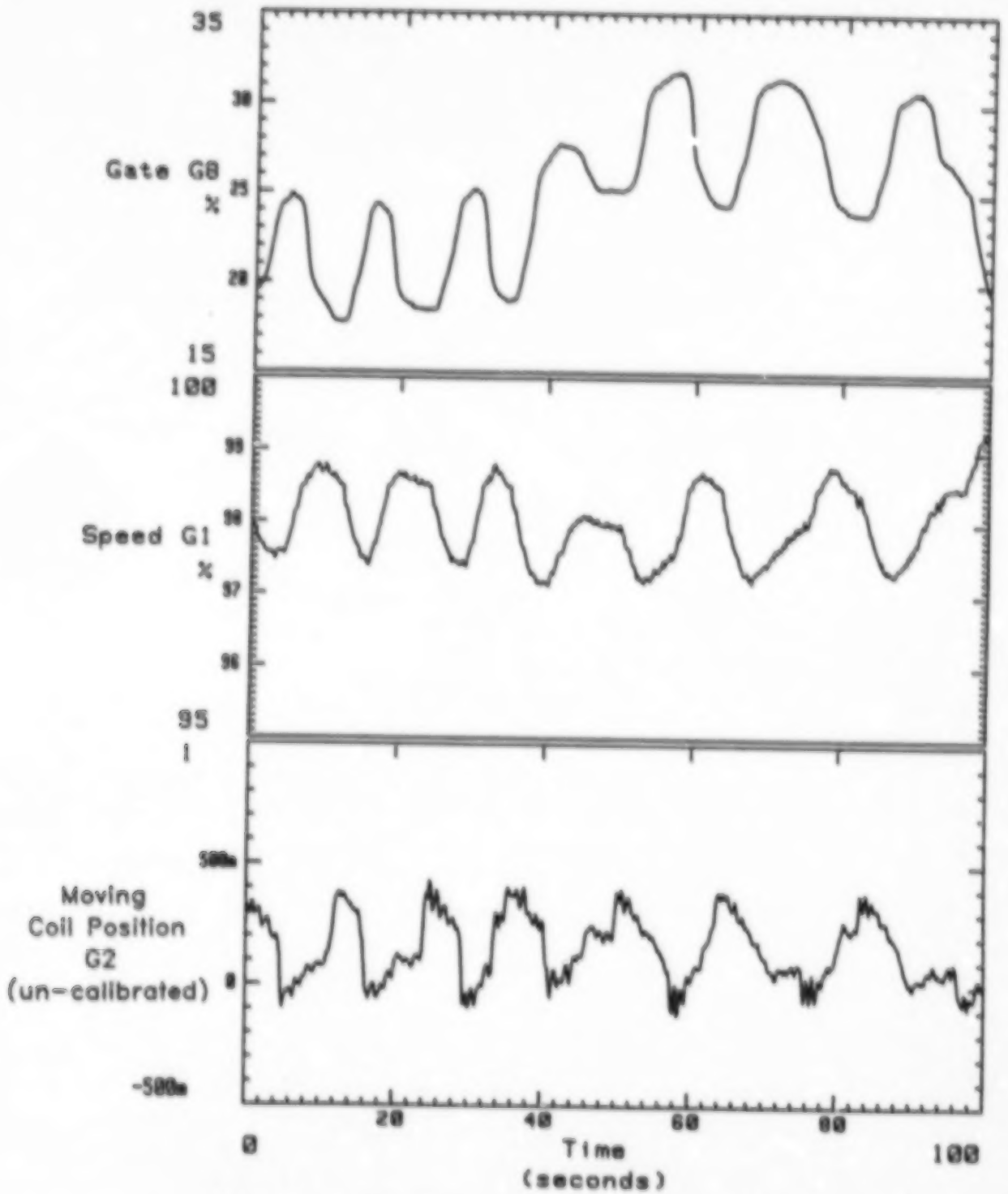
Niagara 25 Hz System Test C2
17 Apr 1989 @ 06:25:00

FIGURE 6d: STELCO EAST (STRIP) MILL LOAD VARIATIONS
BECK I GS MEASUREMENTS



Niagara 25 Hz System Test C2
17 Apr 1989 @ 06:25:00

FIGURE 6e: STELCO EAST (STRIP) MILL LOAD VARIATIONS
BECK I GS MEASUREMENTS



Niagara 25 Hz System Test C2
17 Apr 1989 @ 06:25:00

FIGURE 6f: STELCO EAST (STRIP) MILL LOAD VARIATIONS
BECK I GS MEASUREMENTS

90-309

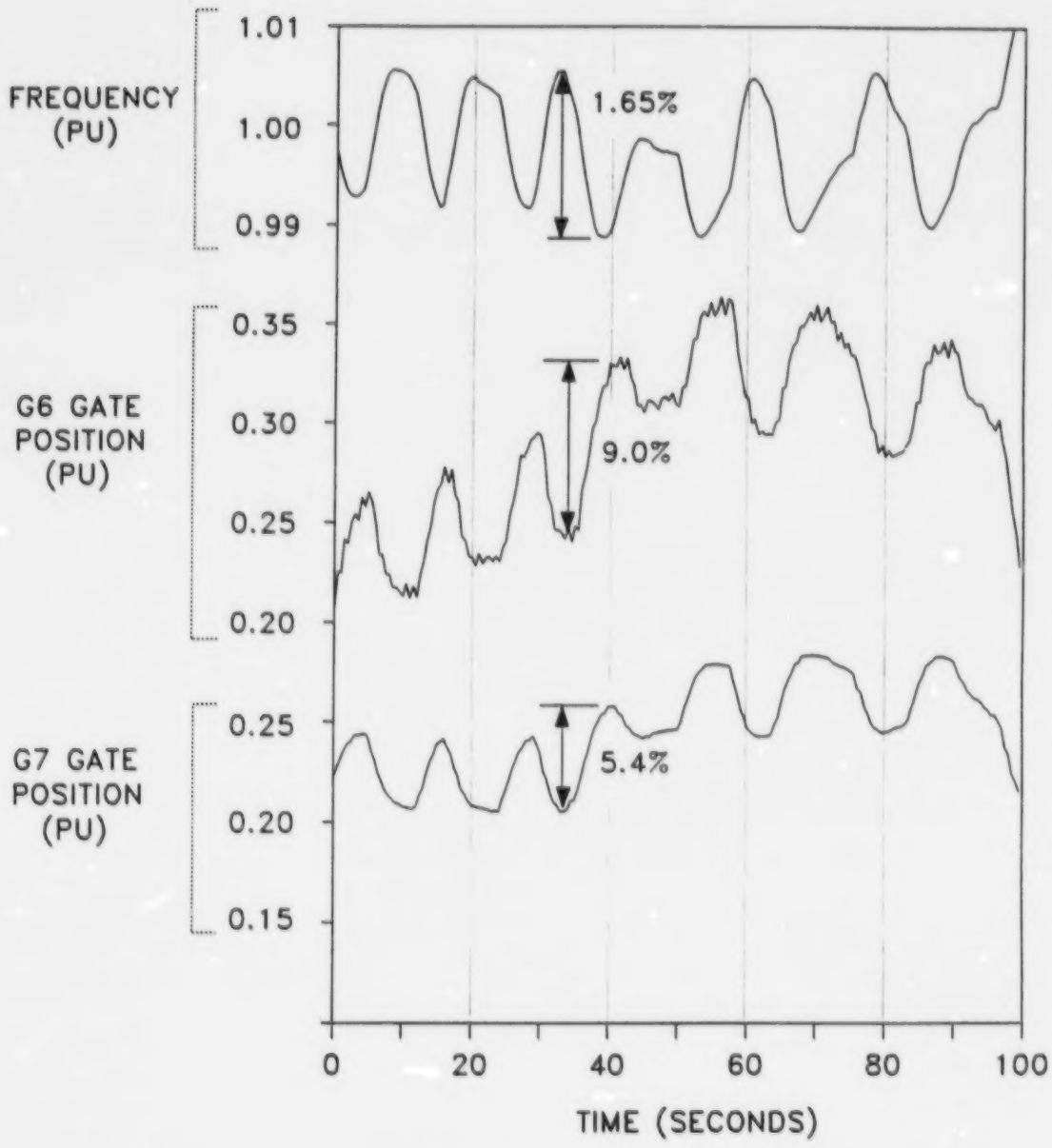
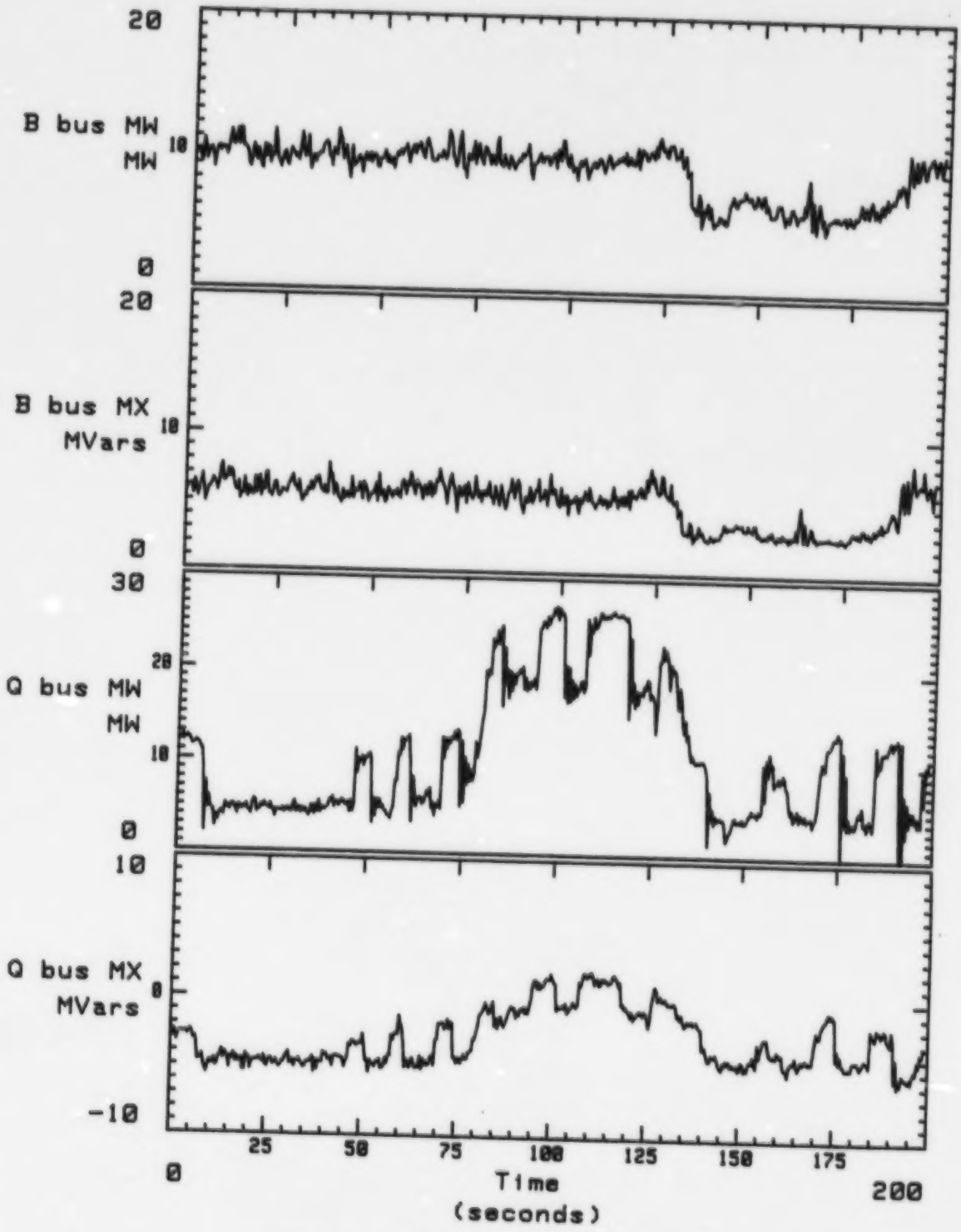
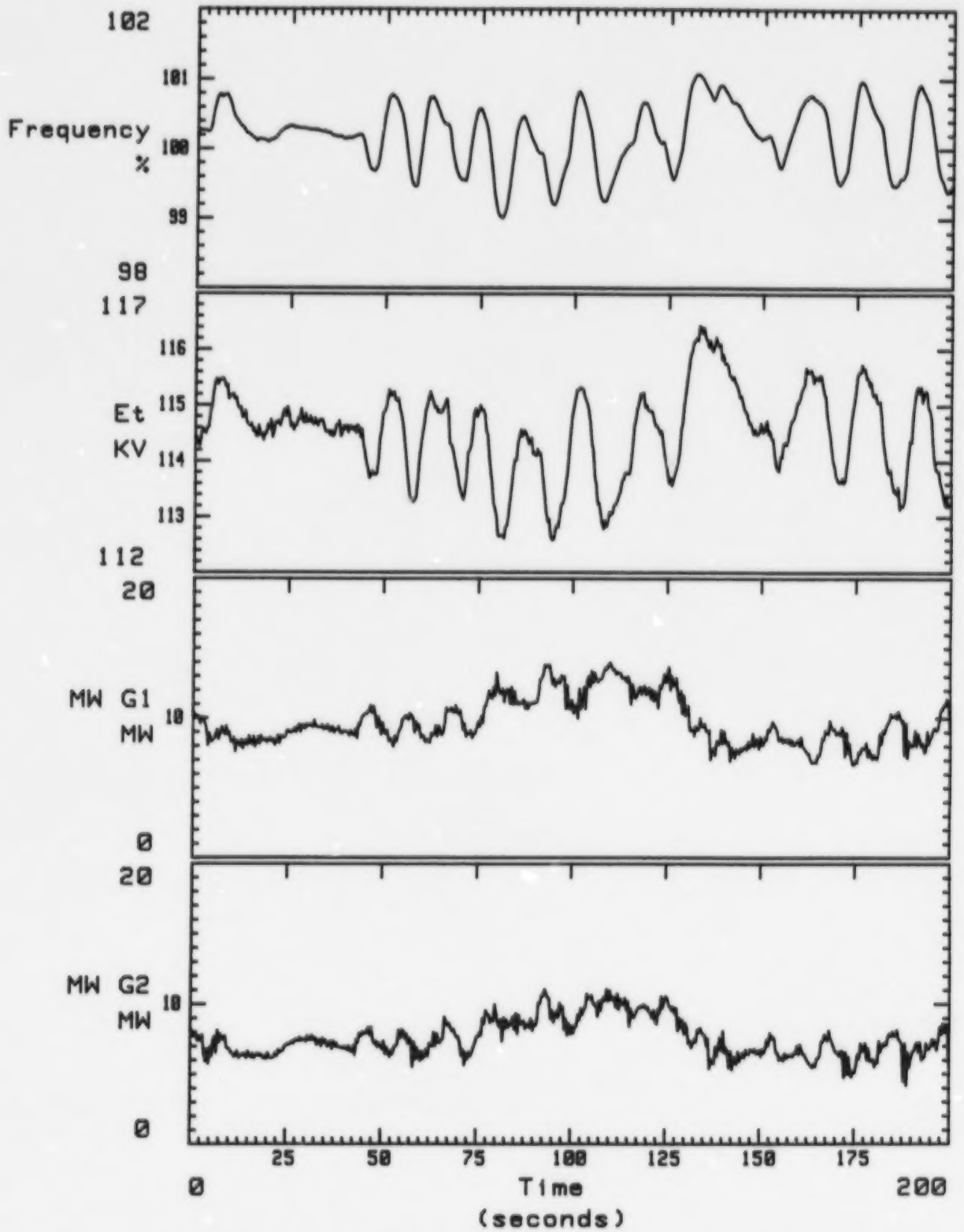


FIGURE 7: FREQUENCY AND GATE POSITION VARIATIONS DURING STELCO STRIP MILL LOAD VARIATIONS



Gage TS Test C9
17 Apr 1989 @ 08:30:00

FIGURE 8a: STELCO LOAD VARIATIONS – MODIFIED GOVERNOR SETTINGS AT BECK I GS

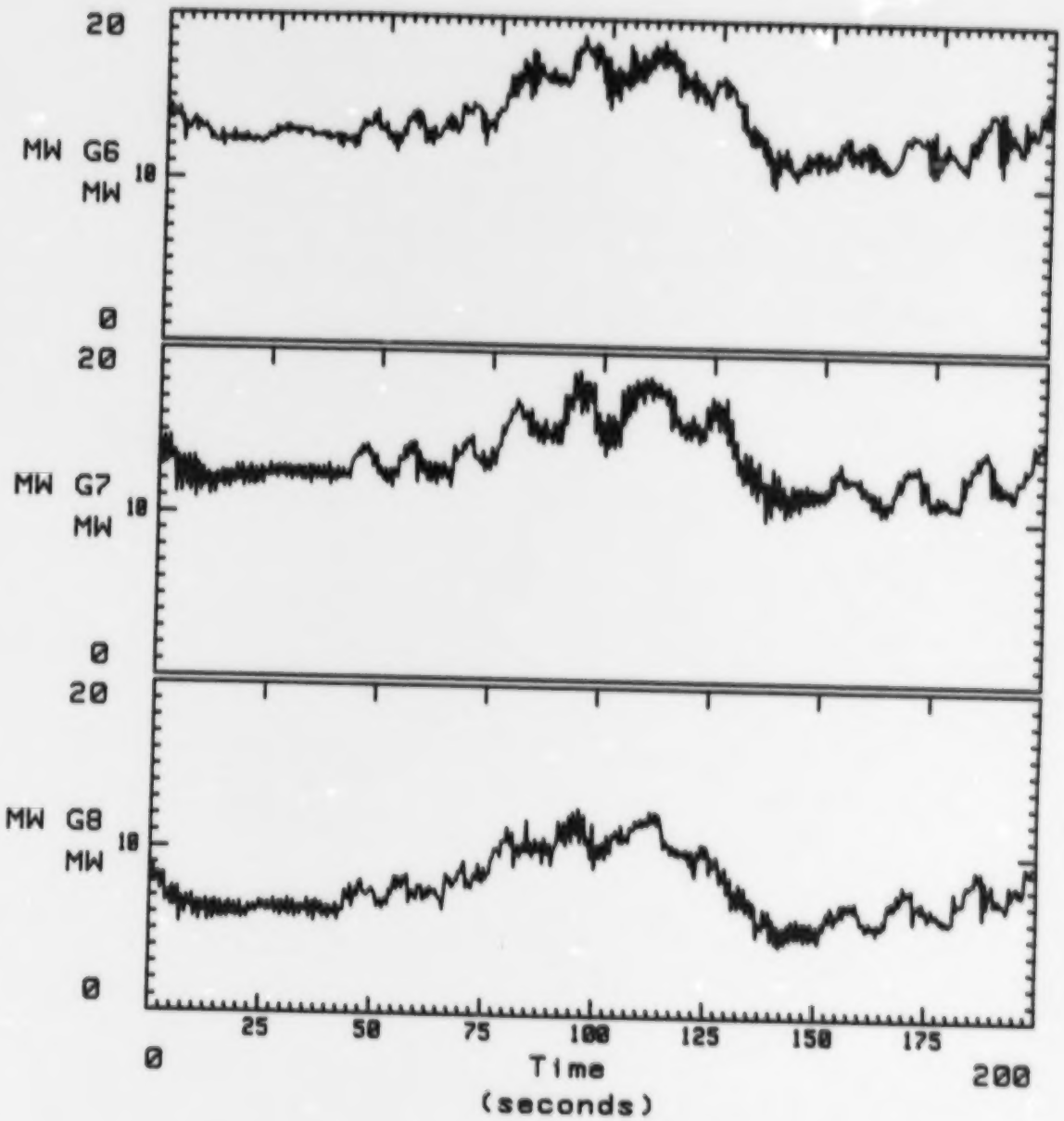


Niagara 25 Hz System Test C9

17 Apr 1989 @ 08:30:00

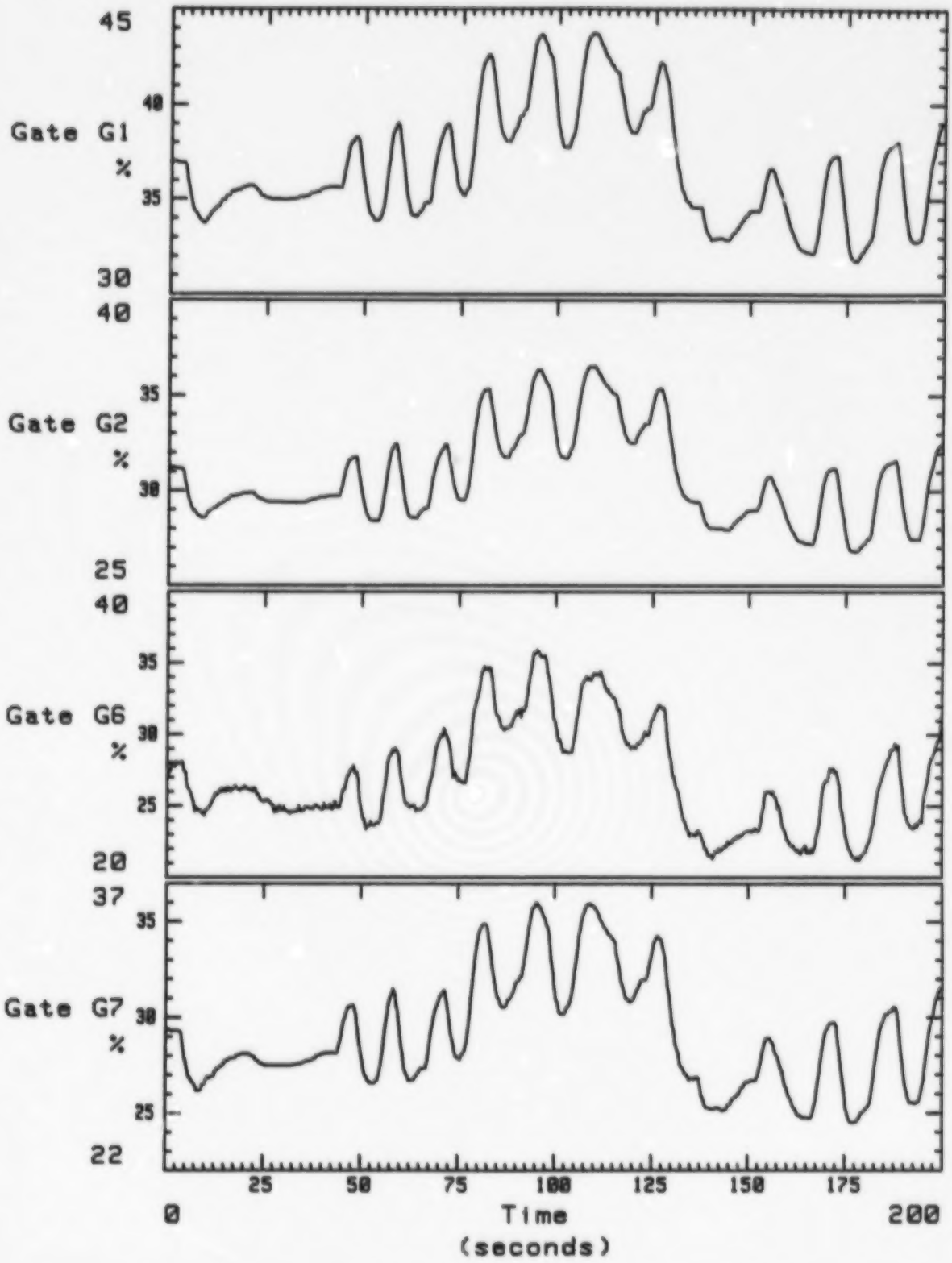
FIGURE 8b: STELCO LOAD VARIATIONS – MODIFIED GOVERNOR SETTINGS AT BECK I GS

90-309



Niagara 25 Hz System Test C9
17 Apr 1989 @ 08:30:00

FIGURE 8c: STELCO LOAD VARIATIONS – MODIFIED GOVERNOR SETTINGS AT BECK I GS

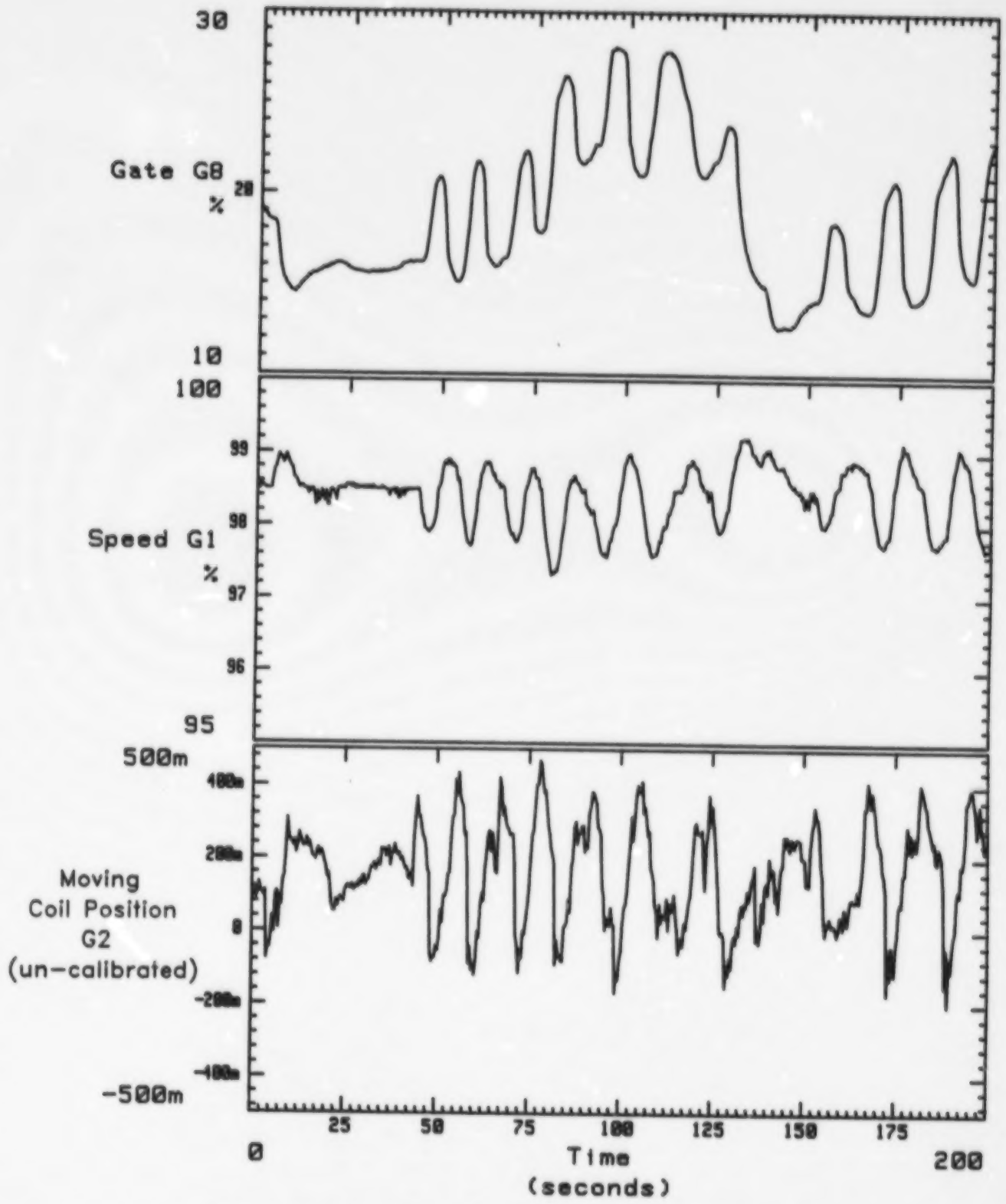


Niagara 25 Hz System Test C9

17 Apr 1989 @ 08:30:00

FIGURE 8d: STELCO LOAD VARIATIONS – MODIFIED GOVERNOR SETTINGS AT BECK I GS

90-309



Niagara 25 Hz System Test C9

17 Apr 1989 @ 08:30:00

FIGURE 8e: STELCO LOAD VARIATIONS – MODIFIED GOVERNOR SETTINGS AT BECK I GS

90-309

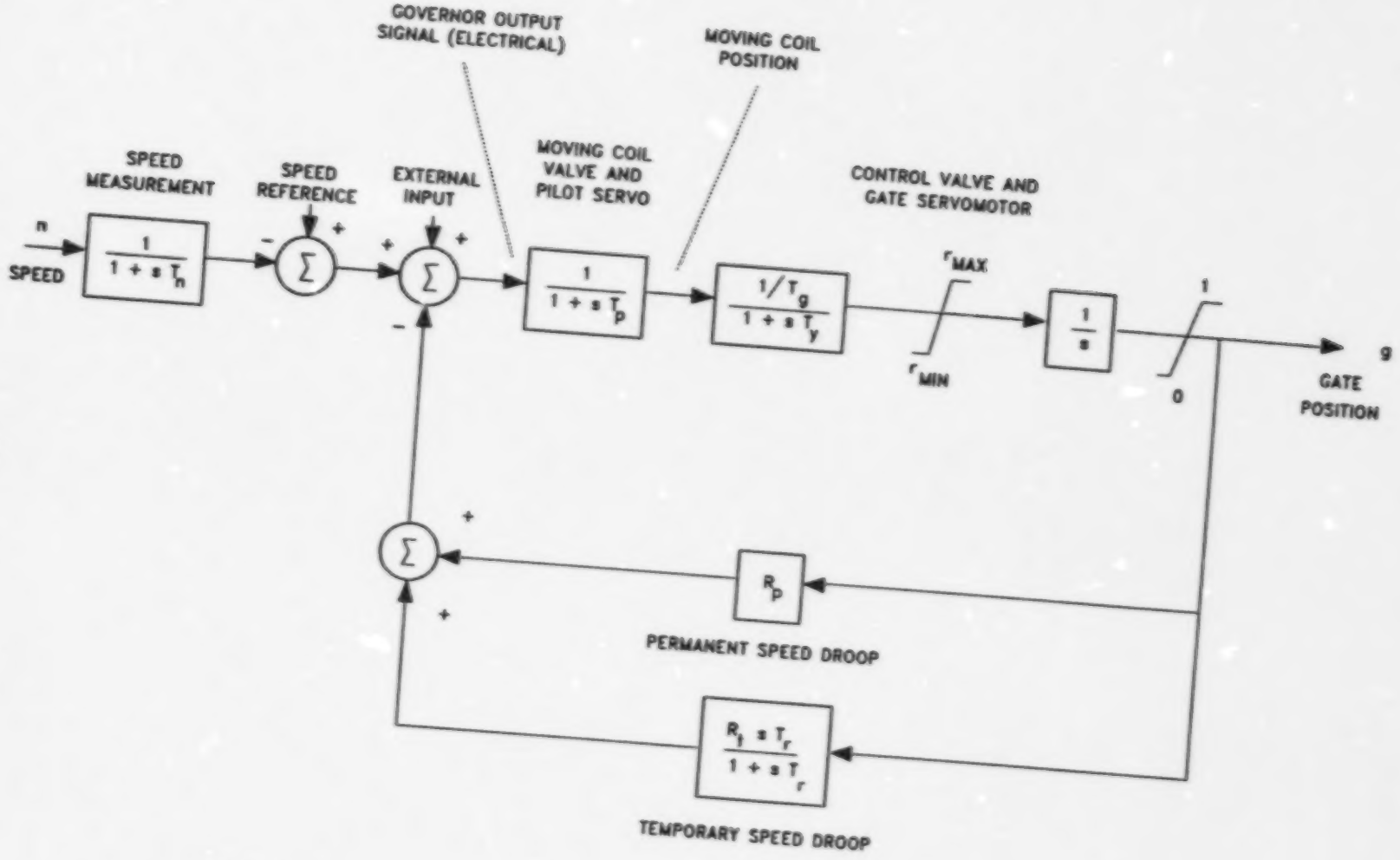


FIGURE 9a : BLOCK DIAGRAM REPRESENTATION OF VOITH ELECTRO–HYDRAULIC GOVERNOR

VOITH31.DRW

FIGURE 9b : SIMPLIFIED REPRESENTATION OF VOITH ELECTRO-HYDRAULIC GOVERNOR

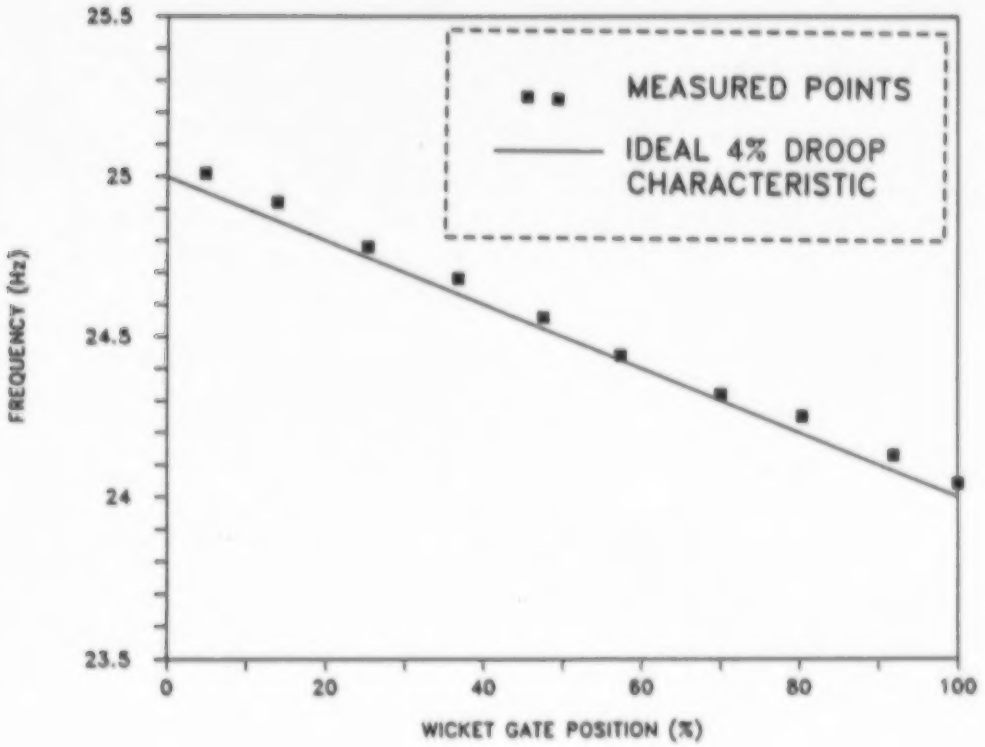


FIGURE 10 : MEASURED INCREMENTAL PERMANENT SPEED DROOP CHARACTERISTIC

UNIT G2, RATED SPEED = 187.5 RPM, NET HEAD = 89.9 m

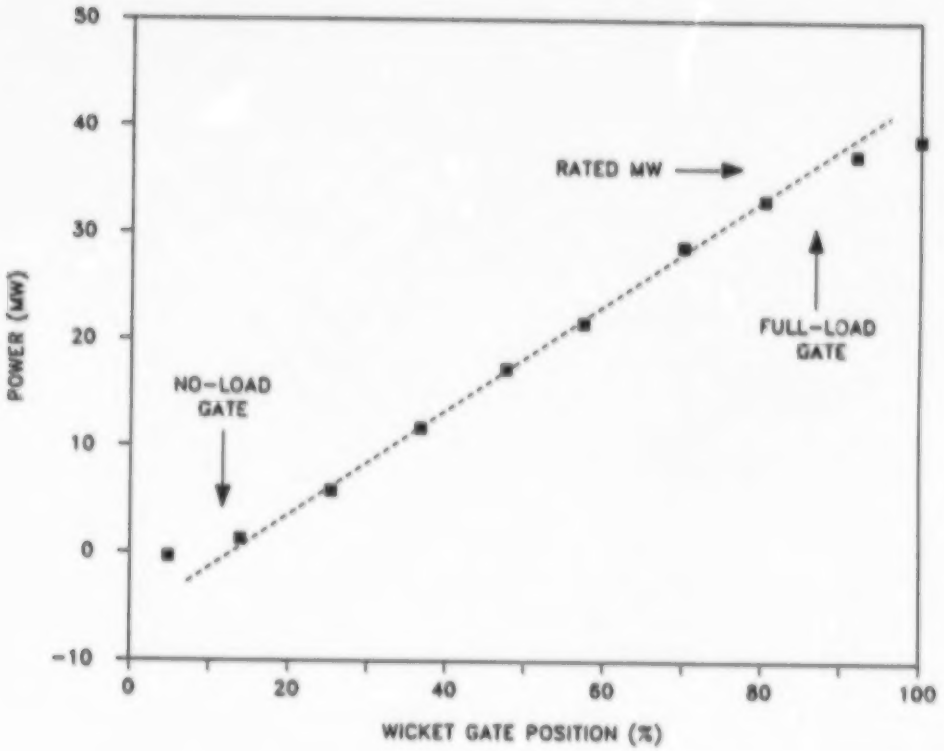


FIGURE 11 : GENERATOR OUTPUT POWER VS. WICKET GATE POSITION

UNIT G2, RATINGS 45 MVA, 0.8 pf, NET HEAD = 89.9 m

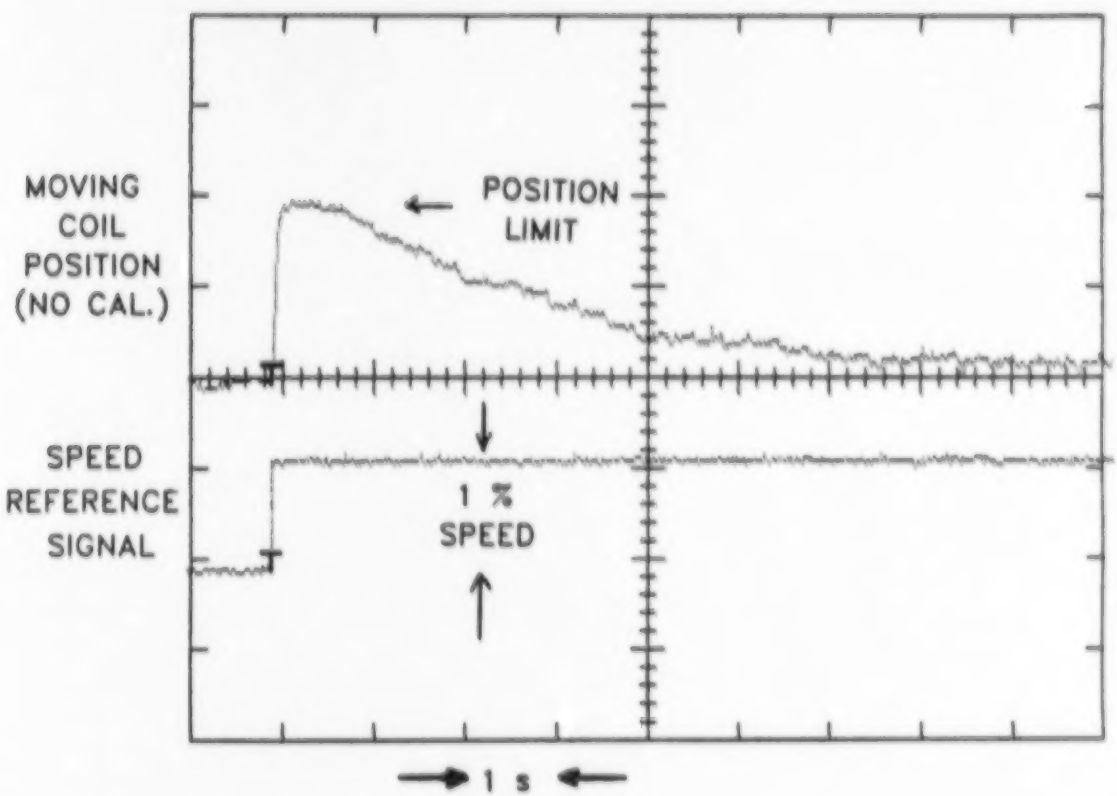


FIGURE 12 : MOVING COIL RESPONSE TO SPEED REFERENCE STEP DISTURBANCE

(S.A. BECK I G2, VOITH GOVERNOR)

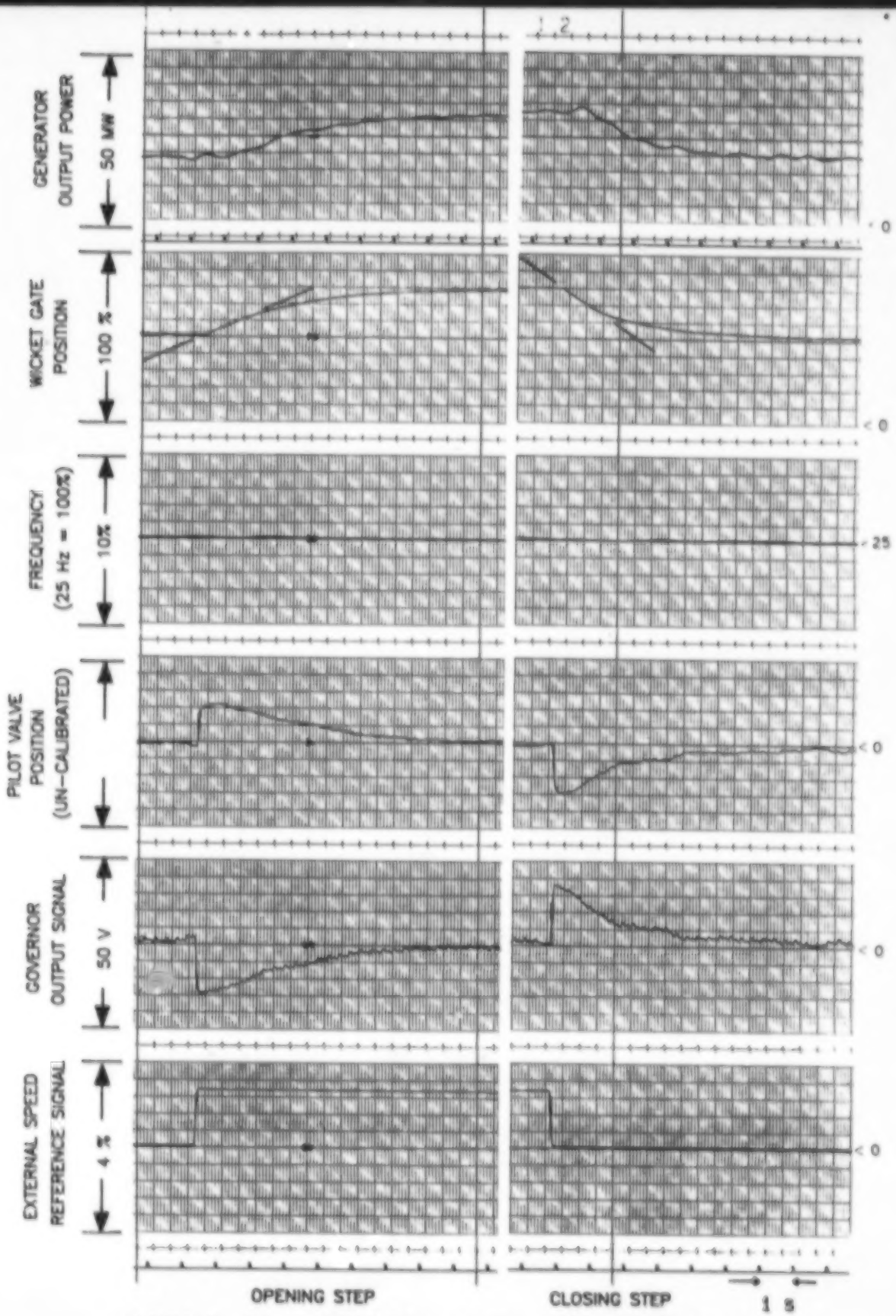


FIGURE 13 : EXTERNAL SPEED REFERENCE STEP DISTURBANCE TEST, S.A.BECK I G2

90-309

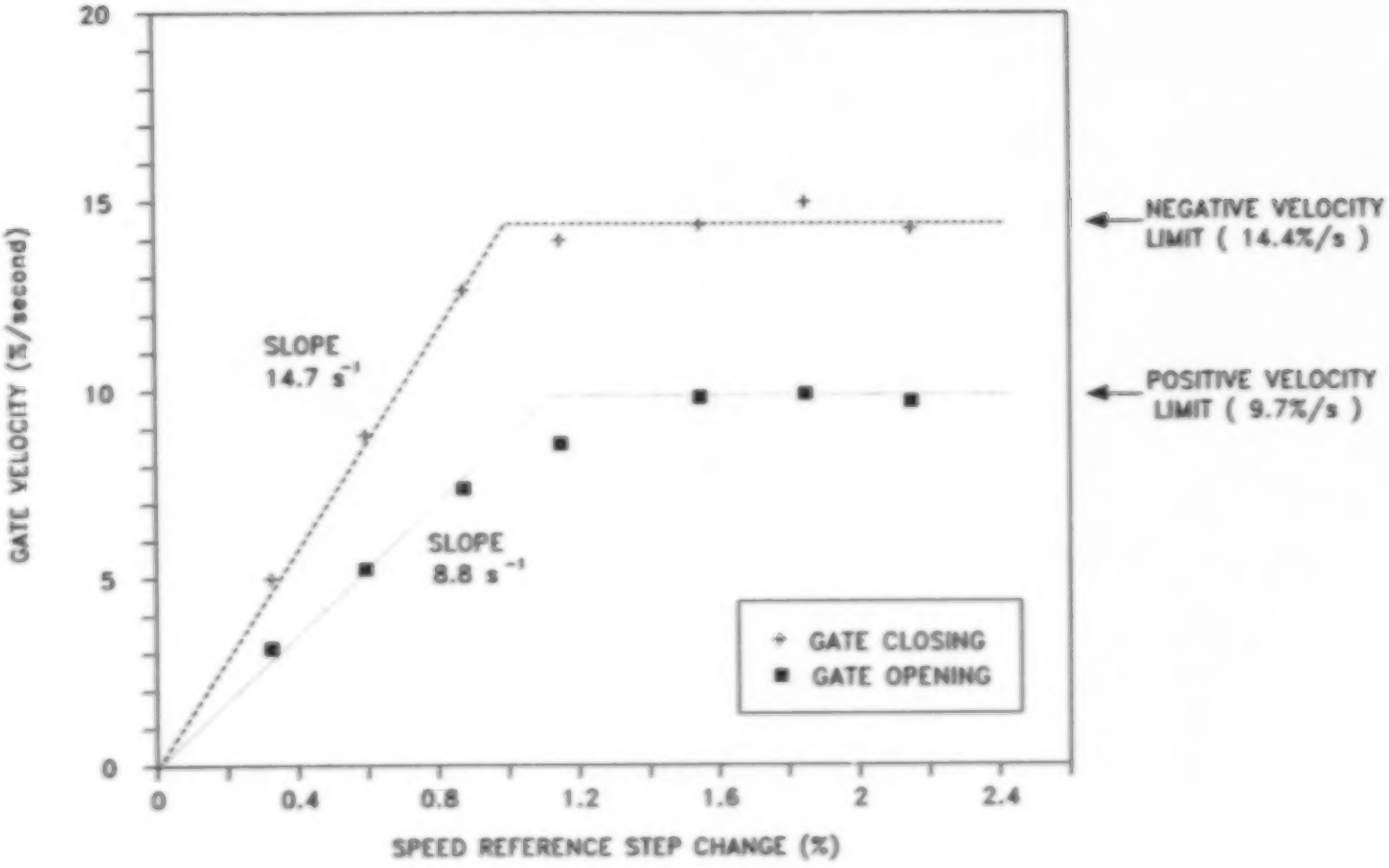


FIGURE 14 : SPEED REFERENCE STEP TEST RESULTS, S.A.BECK G2
DETERMINATION OF GATE VELOCITY LIMITS AND TURBINE GAIN

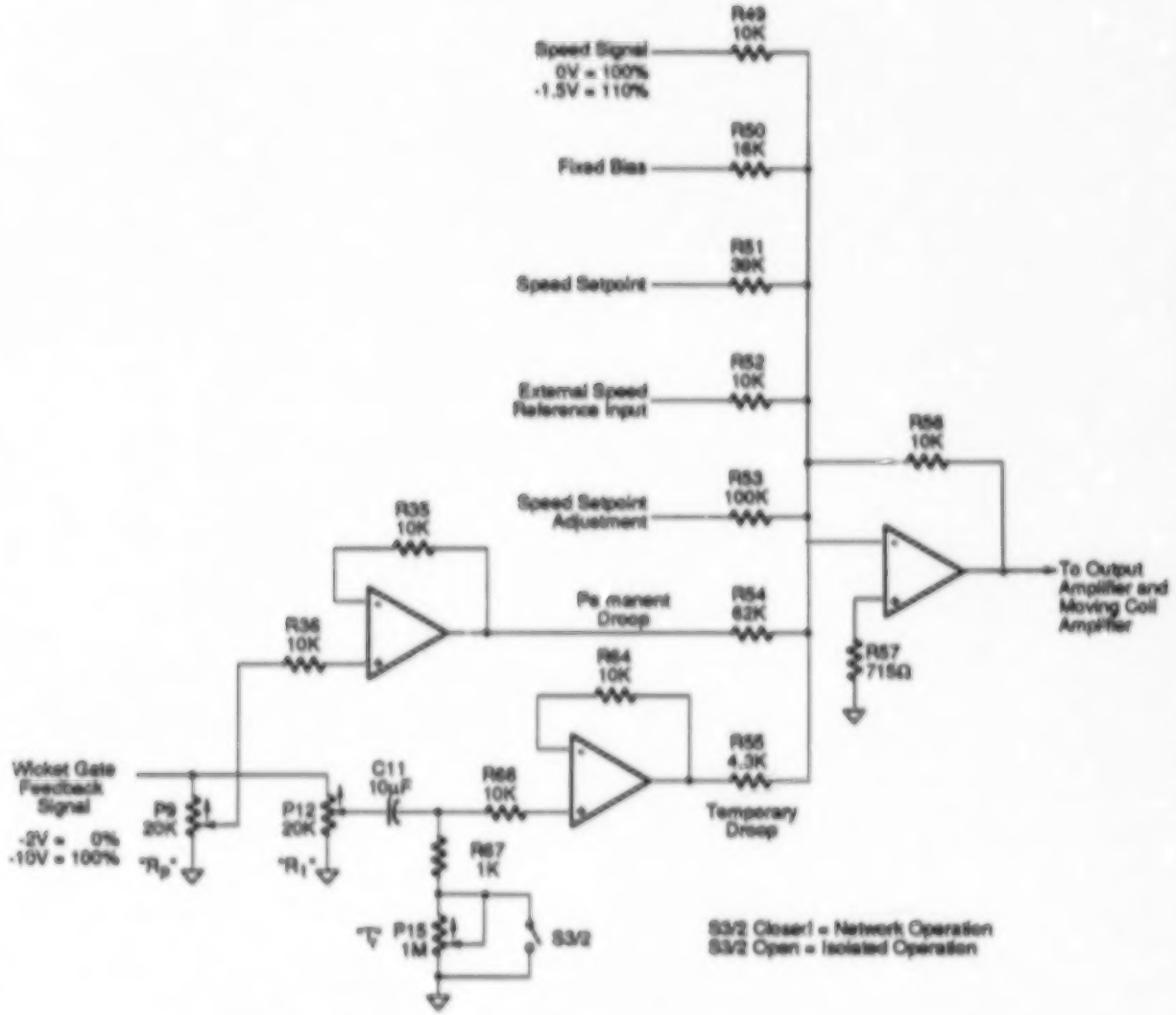


FIGURE 15

VOITH SPEED CONTROL CIRCUIT SIMPLIFIED SCHEMATIC
(based on manufacturer's drawing 2.48 - 1019 / 5)

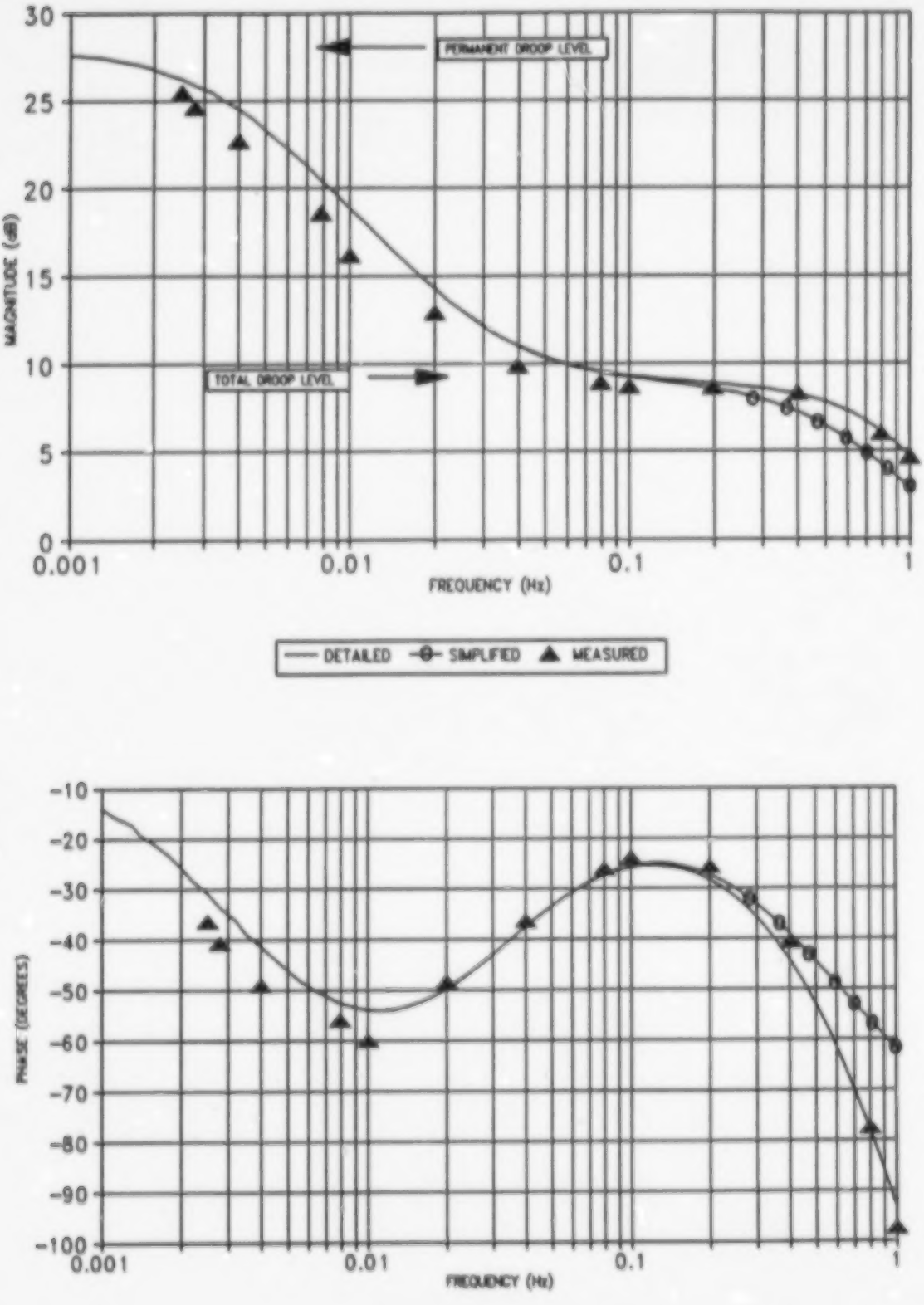


FIGURE 16 : CLOSED-LOOP FREQUENCY RESPONSE, UNIT G2 (VOITH GOV.)

90-309

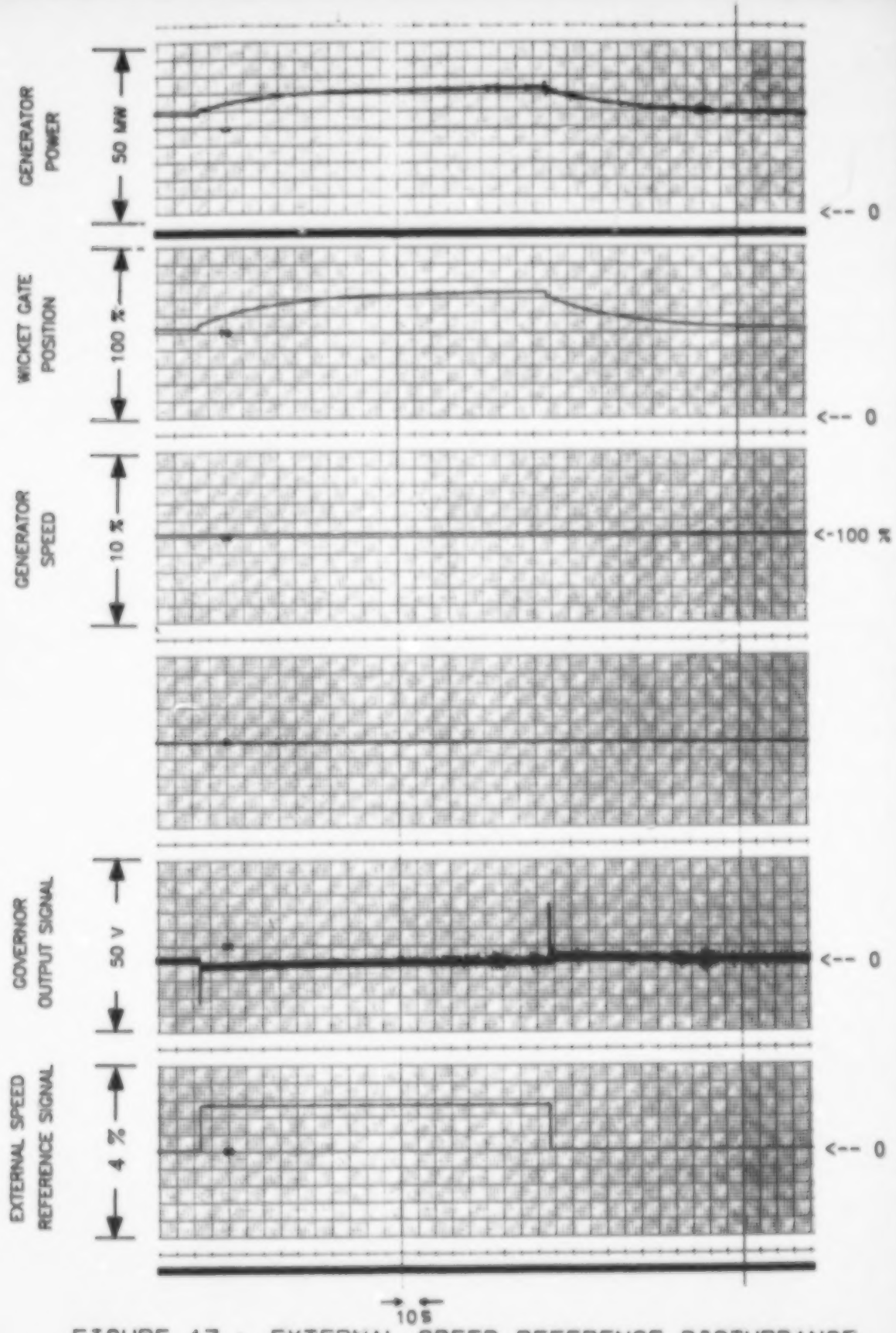


FIGURE 17 : EXTERNAL SPEED REFERENCE DISTURBANCE TEST, G7 - ISOLATED OPERATION SETTINGS

90-309

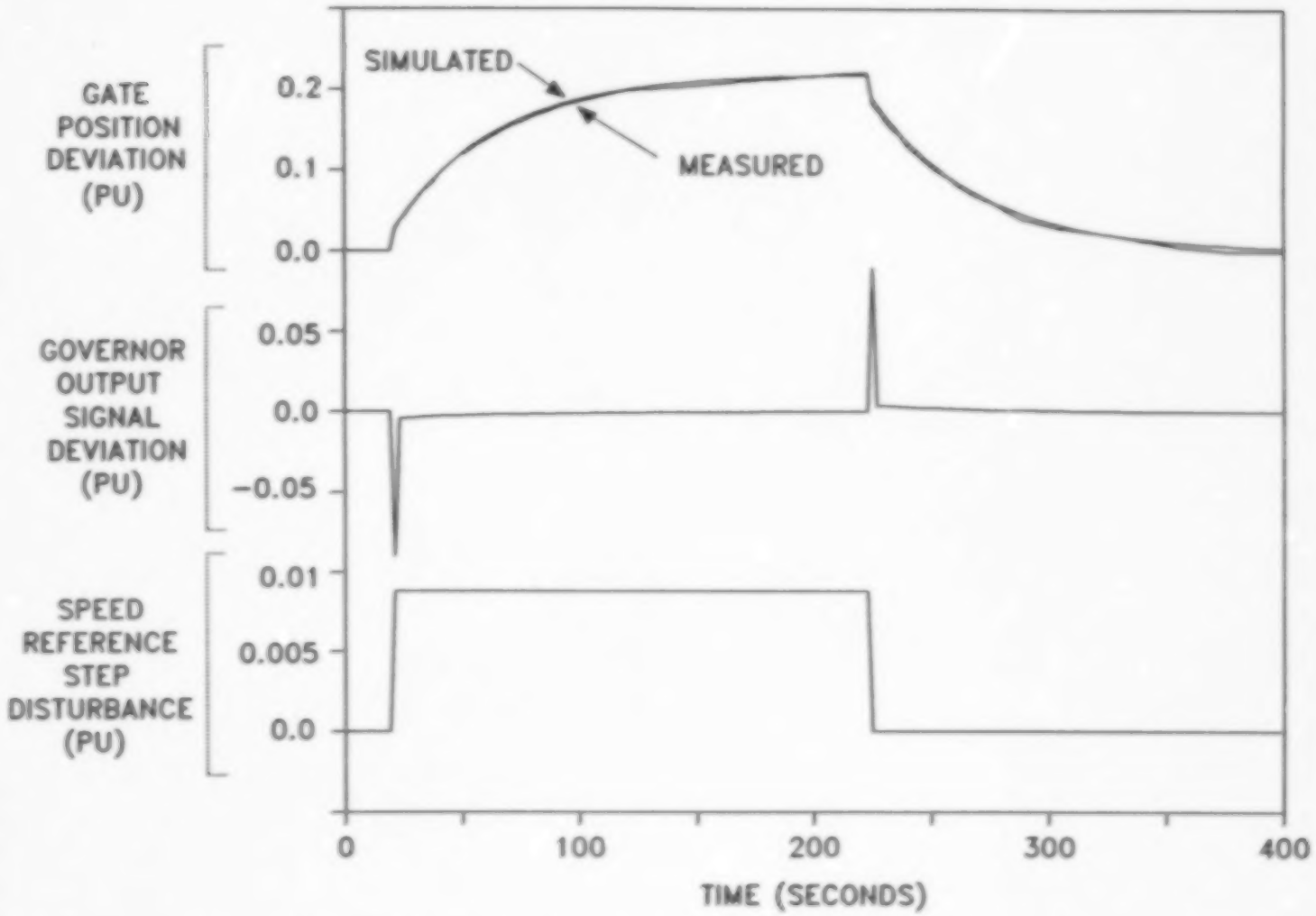


FIGURE 18: SIMULATED ISOLATED OPERATION STEP TEST, UNIT G7

Rt = 0.3 pu, Rp = 0.04 PU, Tr = 5.0 s

FIG18.DRW

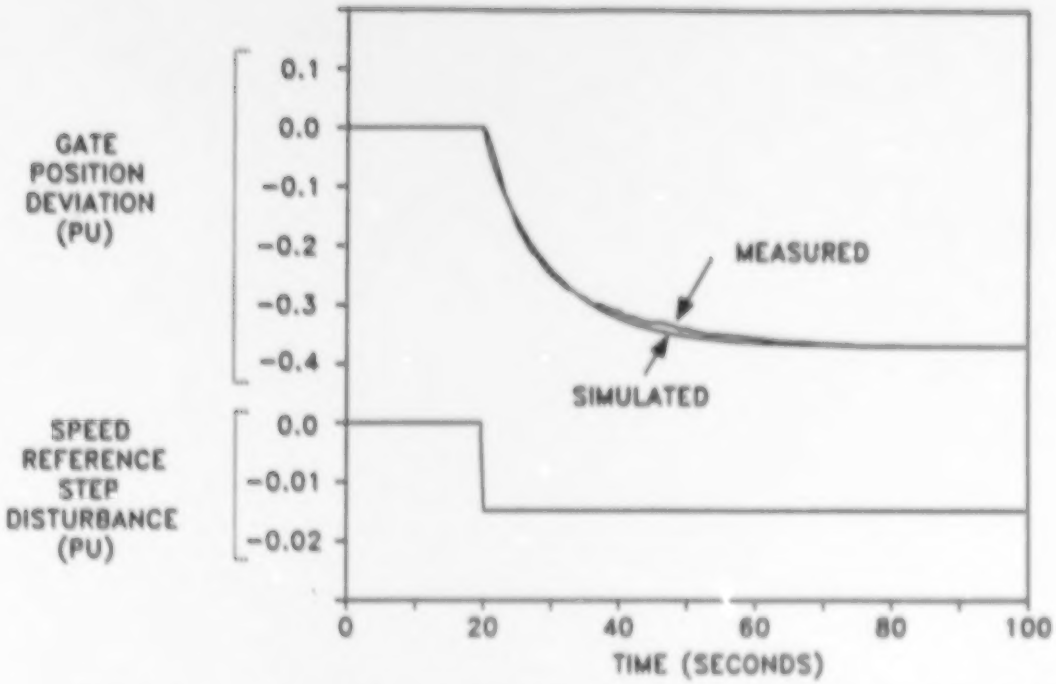


FIGURE 19a: SIMULATED SPEED REFERENCE STEP CHANGE, UNIT G6, Rt=0.15, Tr=2 s

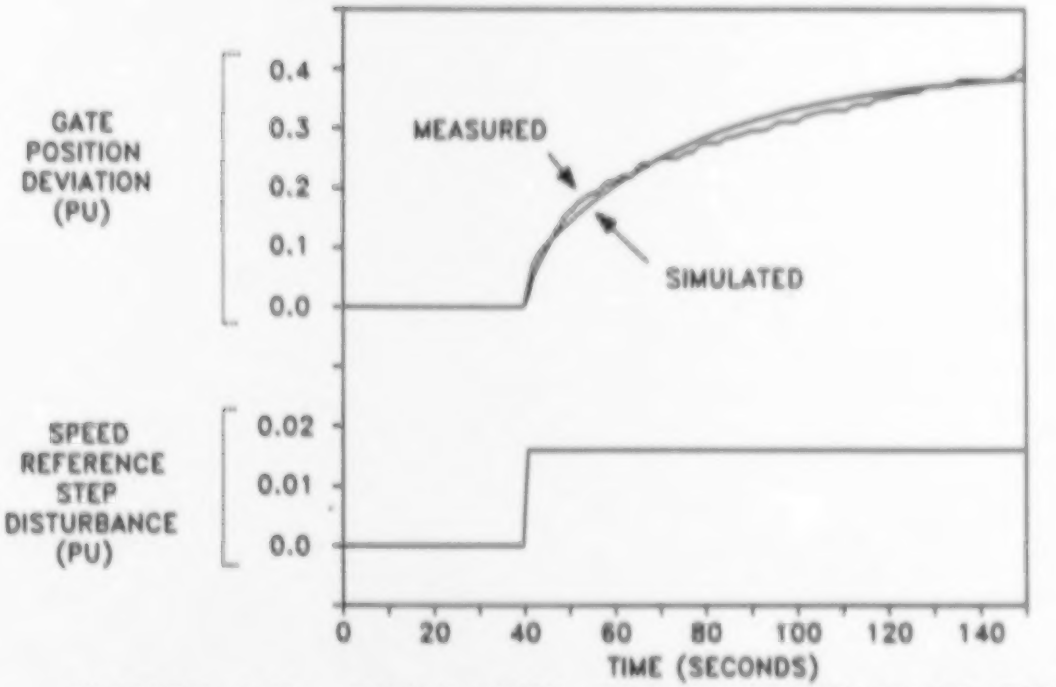


FIGURE 19b: SIMULATED SPEED REFERENCE STEP CHANGE, UNIT G8, Rt=0.15, Tr=7 s

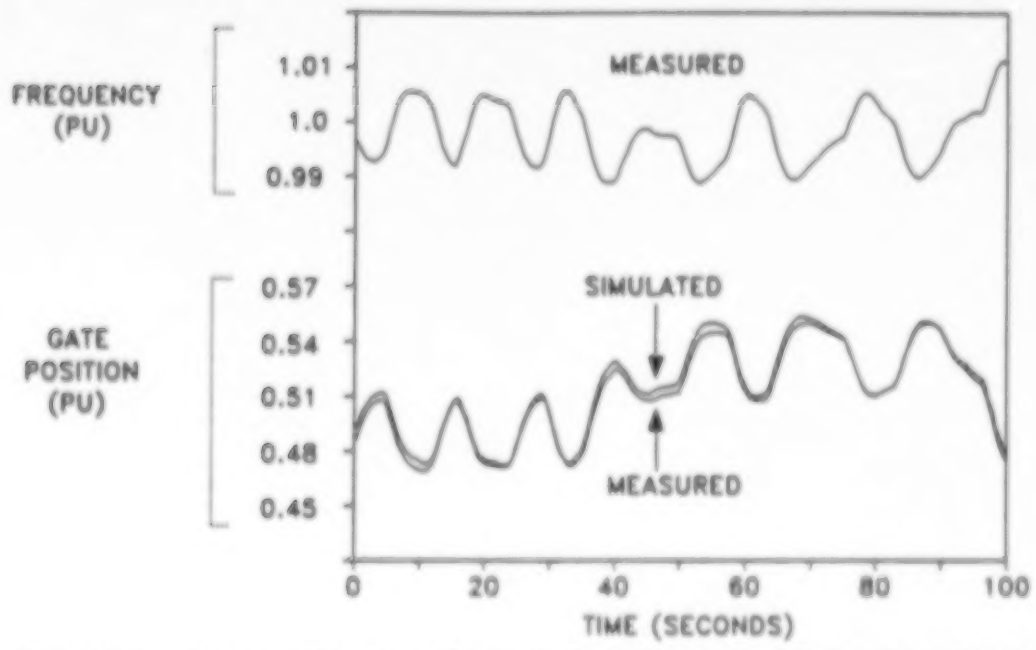


FIGURE 20a: SIMULATED GOVERNOR RESPONSE TO MEASURED FREQUENCY VARIATIONS UNIT G1, Rt=0.3, Rp=0.055, Tr=5 s

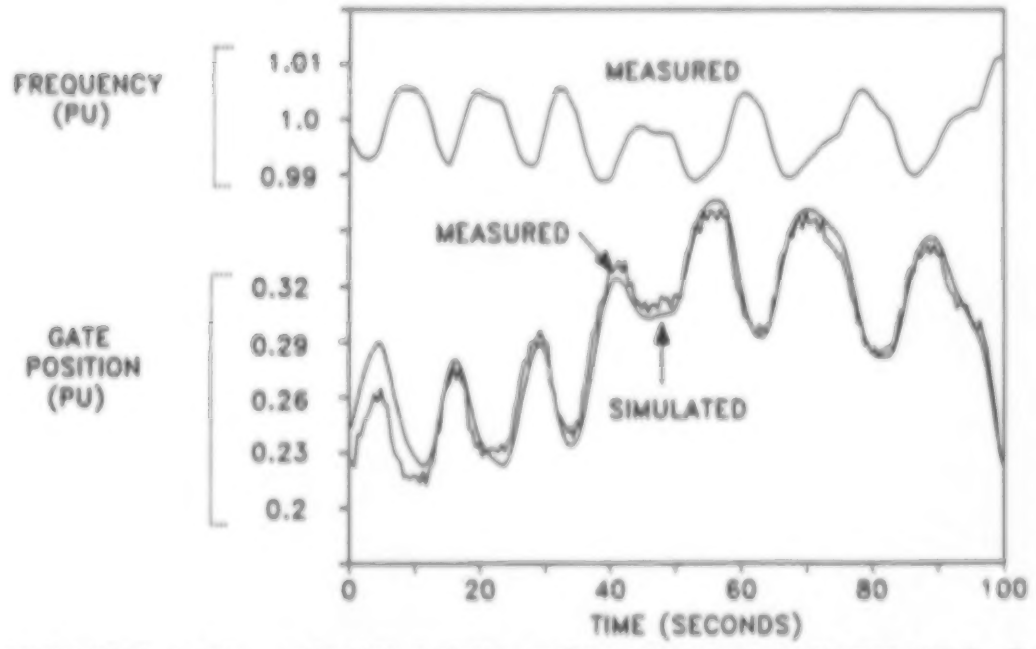


FIGURE 20b: SIMULATED GOVERNOR RESPONSE TO MEASURED FREQUENCY VARIATIONS UNIT G6, Rt=0.15, Rp=0.04, Tr=3 s